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Aircraft Airframe Cost Estimating Relationships

Study Approach and Conclusions

R. W. Hess, H. P. Romanoff

December 1987

RAND | PROJECT AIR FORCE

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A Project AIR FORCE report
prepared for the
United States Air Force

RAND

PREFACE

This report documents the derivation of a set of equations suitable for estimating the acquisition costs of aircraft airframes in the absence of detailed design and manufacturing information. In broad form, this research updates and extends the cost estimating relationships (CERs) published in RAND Report R-1693-1-PA&E, *Parametric Equations for Estimating Aircraft Airframe Costs*, by J. P. Large et al., February 1976, and used in the RAND aircraft cost model, DAPCA, described in R-1854-PR, *A Computer Model for Estimating Development and Procurement Costs of Aircraft (DAPCA-III)*, by H. E. Boren, March 1976. However, it also draws on a number of other studies—RAND and non-RAND—for ideas on how the accuracy and reliability of airframe CERs might be improved.

In the current effort, the A-10, F-15, F-16, F-18, F-101, and S-3 have been added to the estimating sample;[1] the explanatory power of variables describing program structure and airframe construction characteristics is investigated; and the utility of dividing the estimating sample into subsamples representing major differences in aircraft type (e.g., fighter, bomber/transport, and attack aircraft) is examined. Additionally, for the fighter subsample, the possible benefit of incorporating an objective technology measure into the equations is investigated.

To address the issue of sample homogeneity, each of the subsamples, as well as the full sample, had to be investigated in detail, with the ultimate goal of developing a representative set of CERs for each. This report summarizes the results of these individual analyses. Detailed results are available in a series of four companion RAND Notes:

> *Aircraft Airframe Cost Estimating Relationships: All Mission Types*, N-2283/1-AF, by R. W. Hess and H. P. Romanoff, December 1987.

> *Aircraft Airframe Cost Estimating Relationships: Fighters*, N-2283/2-AF, by R. W. Hess and H. P. Romanoff, December 1987.

[1]Also, the F-86, F-89, and F3D, which were dropped from the previous estimating sample (DAPCA-III), were reintroduced.

Aircraft Airframe Cost Estimating Relationships: Bombers and Transports, N-2283/3-AF, by R. W. Hess and H. P. Romanoff, December 1987.

Aircraft Airframe Cost Estimating Relationships: Attack Aircraft, N-2283/4-AF, by R. W. Hess and H. P. Romanoff, December 1987.

This research was undertaken as part of the Project AIR FORCE project entitled "Cost Analysis Methods for Air Force Systems," which has since been superseded by "Air Force Resource and Financial Management Issues for the 1980s" in RAND's Resource Management Program.

While this report was in preparation, Lt. Col. H. P. Romanoff, USAF, was on duty in the System Sciences Department of The RAND Corporation. At present, he is with the Directorate of Advanced Programs in the Office of the Assistant Secretary of the Air Force for Acquisition.

SUMMARY

This report presents generalized equations for estimating the development and production costs of aircraft airframes. It provides separate cost estimating relationships (CERs) for engineering, tooling, manufacturing labor, and quality-control hours; manufacturing material, development support, and flight-test cost; and total program cost. The CERs, expressed in the form of exponential equations, were derived by multiple least-squares regression analysis. They were derived from a database consisting of 34 military aircraft with first flight dates ranging from 1948 to 1978. Most of the aircraft technical data were obtained from either original engineering documents such as manufacturers' performance substantiation reports, or from official Air Force and Navy documents. The cost data were obtained from the airframe manufacturers, either directly from their records or indirectly through standard Department of Defense reports such as the Contractor Cost Data Reporting system.

The equation set that we feel will most accurately reflect the range of estimating situations likely to be encountered in the future utilizes empty weight and speed as the basic size/performance variable combination. It is based on a subsample of the full sample consisting of 13 post-1960 aircraft. We concluded that the more limited post-1960 experience would be a better guide to the future than the cumulative 34-aircraft experience dating back to 1948.

Empty weights for the post-1960 sample aircraft range from under 10,000 lb to over 300,000 lb, while speeds range from 400 kn to over 1,250 kn. The standard errors of estimate of the CERs in the recommended set vary significantly. Four of the CERs (tooling, manufacturing labor, manufacturing material, and total program cost) have standard errors of about 0.30[1] (−26, +35 percent), while three (engineering, development support, and flight test) have standard errors of about 0.50 (−39, +65 percent) or more. None of the equations meets our standard-error-of-estimate goal of 0.18 (−16, +20 percent). On the other hand, the lowest standard errors of estimate in the set are associated with tooling, labor, and material—elements that typically account for 65 to 70 percent of total program cost at an aircraft production quantity of 100.

[1]All standard errors of estimate are originally expressed in logarithmic form; equivalent percentages of corresponding hour or dollar values are provided in parentheses.

The ultimate test of the set's usefulness will be its accuracy for estimating the cost of future aircraft. Unfortunately (from an estimating point of view), dramatic changes are taking place in airframe materials (e.g., more extensive use of composites), design concepts (e.g., to increase fuel efficiency and to reduce radar cross section), resources devoted to system integration (e.g., integration of increasingly sophisticated electronics and armament into the airframe), and manufacturing techniques (e.g., utilization of computers and robots). And although we do not have the data to demonstrate it, we believe that the net effect of these changes will be to increase unit costs. In other words, we see little danger that the recommended equation set will overestimate the costs of future aircraft.

In addition to the basic objective of developing an updated set of airframe CERs, this study also examined in some detail the following possibilities for improving CER accuracy:

- Stratifying the full estimating sample into subsamples representing major differences in aircraft type.
- Incorporating variables describing program structure and airframe construction characteristics into the CERs.
- For the fighter aircraft only, incorporating an objective technology index into the equations.

We examined subsamples of aircraft categorized by mission designation—fighter, bomber/transport, and attack—to evaluate the effects of stratification, and we concluded that this approach offers no particular advantage. In fact, we were not able to identify any acceptable estimating relationships for either the bomber/transport or the attack aircraft subsamples. For the fighter subsample, the equation set that we felt was most likely to be representative of future fighter programs consisted of a series of simple weight-scaling relationships that were visually fit to the subset of post-1960 fighters (F-4, F-111, F-14, F-15, F-16, and F-18). In general, this set of equations will produce higher estimates than the all-mission-type equation set for relatively light, "slow" fighters[2] (e.g., the F-16 and F-18) and lower estimates for relatively heavy, fast fighters (e.g., the F-4, F-111, F-14, and F-15). However, we found that the fighter equation set was only slightly more accurate overall than the all-mission-type set, despite its much more concentrated focus.

We concluded that incorporating variables describing program structure and airframe construction characteristics (at least as we have defined them) does not improve the overall quality of the equation sets.

[2]Under Mach 2.

Although variables characterizing the level of system integration were frequently found to be statistically significant, they did not, as a rule, result in any substantial improvement in the quality of the equations. In most cases, the equations incorporating such variables did not produce results that we viewed as credible. Moreover, even in those few instances where the equations did produce credible results, the reduction in the standard error of estimate was never more than two or three percentage points.

Finally, attempts to incorporate an objective technology index into the fighter cost estimating relationships were unsuccessful.

ACKNOWLEDGMENTS

The authors owe a considerable debt to a number of individuals. Foremost among these are RAND colleagues Joseph Large and William Stanley, who were never too busy to answer our seemingly unending questions or to offer helpful suggestions. Giles Smith and Richard Stanton, also of RAND, provided insightful technical reviews that considerably enhanced the quality of the final report. Finally, individuals at a dozen aircraft companies provided informal review and comment on earlier drafts and granted us permission to publish cost data that had previously been regarded as proprietary. We express our appreciation to the following companies for their invaluable cooperation:

Boeing Military Airplane Company
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Fairchild Republic Company
Grumman Aerospace Corporation
General Dynamics Corporation/Convair Division
General Dynamics Corporation/Fort Worth Division
Lockheed-California Company
Lockheed-Georgia Company
McDonnell Aircraft Company
Northrop Corporation
Rockwell International Corporation/North American Aircraft
Vought Corporation

CONTENTS

ACRONYMS AND ABBREVIATIONS

AUW	Airframe unit weight (lb)
CA	Cumulative average
CARGODV	Cargo aircraft designator (1 = no; 2 = yes)
DS	Development support cost (thousands of 1977 dollars)
$ENGR_{100}$	Cumulative engineering hours for 100 aircraft (thousands)
$ENGRC_1$	Nonrecurring engineering cost (thousands of 1977 dollars)
EW	Empty weight (lb)
F	F-statistic
FFD	Actual first flight date (months since January 1, 1940)
FT	Flight-test cost (thousands of 1977 dollars)
$LABR_{100}$	Cumulative manufacturing labor hours for 100 aircraft (thousands)
$MATL_{100}$	Cumulative manufacturing material costs for 100 aircraft (thousands of 1977 dollars)
N	Number of observations
PFFD	Predicted first flight date (months since January 1, 1940)
$PROG_{100}$	Cumulative total program cost for 100 aircraft (thousands of 1977 dollars)
Q	Quantity
QC_{100}	Cumulative quality control hours for 100 aircraft (thousands)
R^2	Coefficient of determination
SEE	Standard error of estimate
SP	Maximum speed (kn)
SPPWR	Specific power (hp/lb)
TESTAC	Number of flight-test aircraft
$TOOL_{100}$	Cumulative tooling hours for 100 aircraft (thousands)

FIGURES

TABLES

I. INTRODUCTION

Parametric models for estimating aircraft airframe acquisition costs have been used extensively in advanced planning studies and contractor proposal validation. These models are designed to be used when little is known about an aircraft design or when a readily applied validity and consistency check of detailed cost estimates[1] is necessary. They require inputs that (a) will provide relatively accurate results, (b) are logically related to cost, and (c) can easily be projected before actual design and development information is available. Their purpose is to generate estimates that include the costs of program delays, engineering changes, data requirements, and all kinds of phenomena that occur in a normal aircraft program.

Since 1966, RAND has developed three parametric airframe cost models.[2] These models have been characterized by (a) easily obtainable size and performance inputs (weight and speed), (b) the estimation of costs at the total airframe level, and (c) the utilization of heterogeneous aircraft samples. They have usually been updated when enough additional aircraft data points have become available to suggest possible changes in the equations. In the present model, the A-10, F-15, F-16, F-18, F-101, and S-3 have been added to the full estimating sample.[3]

Analysts at several other companies have also attempted to develop more accurate parametric models. Some of these projects are listed in Table 1.

The models in Table 1 vary somewhat with respect to specific purpose, level of detail, and sample size and type.[4] Consequently, before undertaking this update of the RAND airframe equations, we reviewed each model reference document for potential means of improving accuracy. Three possibilities emerged from this review:

- Use of a more homogeneous sample such as a single mission type (e.g., fighter, bomber, transport, or attack aircraft).

[1]Examples of this latter application include the Independent Cost Analysis (ICA) prepared as part of the Defense Systems Acquisition Review Council (DSARC) process, and government analyses of contractor cost proposals during source selections.

[2]See Refs. 1, 2, and 3.

[3]In addition, the F-86, F-89, and F3D, which were dropped from the previous estimating sample (that of DAPCA-III), were reintroduced.

[4]A critique of the RAND, PRC, Noah, and SAI models is given in Ref. 11.

Table 1

CONTRACTOR EFFORTS TO IMPROVE PARAMETRIC COST ESTIMATING MODELS

Developer	Sponsor	Year	Ref.
Planning Research Corporation (PRC)	OSD	1967	4
J. Watson Noah Associates	Navy	1973	5
J. Watson Noah Associates	Navy	1977	6
Science Applications, Inc. (SAI)	NASA	1977	7
General Dynamics (Convair)	AF	1975	8
General Dynamics (Convair)	AF	1977	9
Grumman Aircraft	AF	1978	10

- Incorporation of an objective technology index into the cost estimating relationships (CERs).
- Incorporation of construction and program characteristics into the CERs (e.g., wing type, internal density, contractor experience, type of development program).

We investigated each of these approaches to determine its potential utility for developing a set[5] of equations for estimating airframe costs. The rationale for each approach is discussed below.

POSSIBLE APPROACHES FOR IMPROVING MODEL ACCURACY

Sample Homogeneity

Other things being equal, it is clearly preferable to work with a homogeneous sample rather than one that contains diverse and perhaps misleading data points. The difficulty in developing such a sample for military aircraft arises in defining sets of characteristics that are capable of classifying these aircraft in terms that bear some rational relationship to cost. This study was based on a fairly straightforward method for stratification, mission designation (i.e., attack, bomber/transport, and fighter). Generally speaking, fighters tend to be smaller, faster, and more maneuverable than other types of mission aircraft. Attack aircraft, on the other hand, tend to be larger, slower, and less maneuverable, because of greater emphasis on range/payload performance. Finally, bomber/transport aircraft tend to be the largest, slowest, and least maneuverable of the aircraft types.

[5]A set encompasses the following cost elements: engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control.

This type of classification does result in anomalies. For example, a fighter may be larger than a bomber (F-111 airframe unit weight exceeds B-58 airframe unit weight), and a bomber may be faster than a fighter (B-58 speed exceeds F-102 speed). Furthermore, the missions of two aircraft with the same designation can be quite dissimilar; for example, while the primary mission of most fighters is air-to-air, the primary mission of some, such as the F-105 and F-111, is air-to-ground, which may in fact make them more akin to attack aircraft than fighters. Unfortunately, these definitional difficulties are not easily rectified (the more restrictive, or pure, the definition, the smaller the sample size). They are noted here only to illustrate that such problems do exist.

Technology Index

Previous RAND analyses have suggested that the relative accuracy of acquisition cost and schedule estimates made at the beginning of major weapon system development programs is at least partially influenced by the degree of technological advance being sought.[6] As a first step toward a better understanding of this relationship, a technique was developed for objectively quantifying the technological state of the art of one particular type of system, aircraft turbine engines.[7] Subsequent analysis established a functional relationship between the technology embodied in engine designs and their acquisition costs, resulting in improved CERs for aircraft turbine engines.[8]

More recent work has attempted to quantify the technological change in U.S. jet fighter aircraft.[9] An expression was developed that related the time of appearance of an aircraft design to its level of performance, which is interpreted as a measure of its level of technological sophistication.[10] The expression, which includes specific power, the Breguet range factor, sustained load factor, fuel fraction, and a carrier-capability designator, is illustrated in Fig. 1, where:

> The vertical axis measures the first flight date calculated by inserting aircraft performance parameters in the technology equation and the horizontal axis measures the actual first flight date for each aircraft. The distribution of the 25 data points about the 45 degree line

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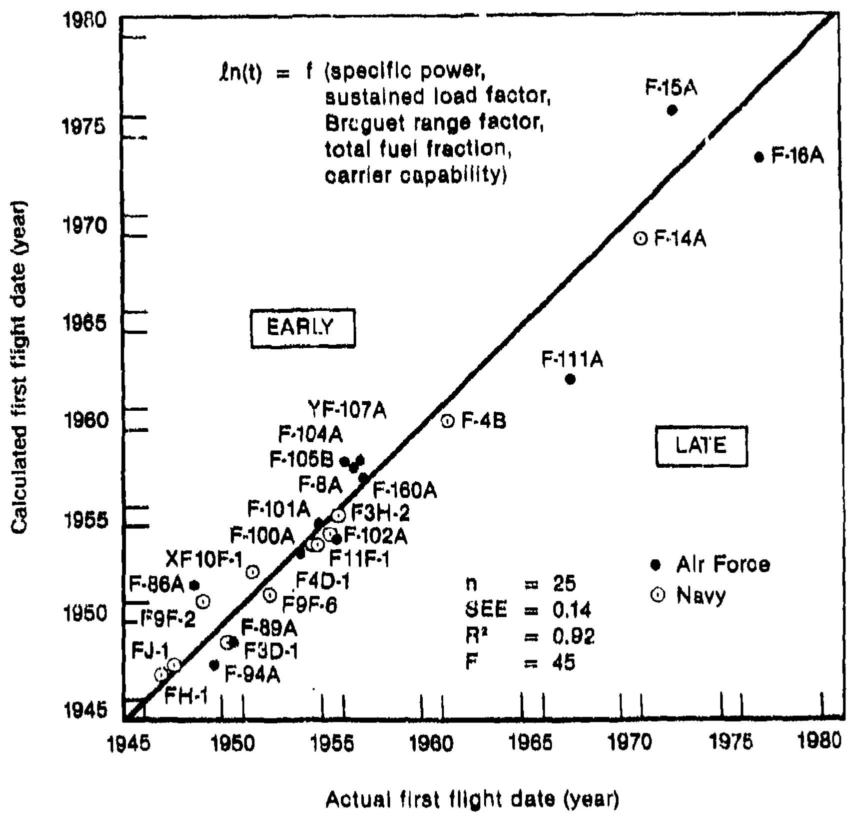
[6]See Refs. 12 and 13.

[7]See Ref. 14.

[8]See Refs. 15 and 16.

[9]See Ref. 17.

[10]In addition to the technology index itself, another benefit of the technology study to this analysis was the identification of several individual explanatory variables which had not previously been tested for significance in airframe cost equations.



$$\ln(t) = 3.530 + .059\left[\frac{\text{Thrust} \quad V_{max}}{100W_{cbt}}\right] + 1.768\left[\frac{\text{Breguet range factor}}{10{,}000}\right] + 1.186\left[\frac{\text{Sustained load factor}}{10}\right]$$

$$+ .526\left[\begin{array}{c}\text{Total}\\ \text{fuel}\\ \text{fraction}\end{array}\right] - .168\left[\begin{array}{c}\text{Carrier}\\ \text{capability}\end{array}\right]$$

NOTE: t = calculated first flight date measured in months since January 1, 1940. Thrust measured in pounds, V_{max} in knots, combat weight in pounds. Carrier capability variable: 1 denotes no capability, 0 denotes capability.

Fig. 1—Multivariate technology trend for new fighter designs

> provides one measure of how well the equation fits the data sample. Points plotted above the 45 degree line represent aircraft that flew earlier than the date predicted by the equation, and the converse holds for points plotted below the line. The magnitude and sign of the residual of the technology equation determine where a particular aircraft point falls relative to the 45 degree trend line, with the residual representing all the unquantifiable factors that influence when the first flight of an aircraft occurs, including technological factors not covered by the independent variable parameter set, scheduling decisions, Congressional and service funding decisions, development philosophy, etc. Accordingly, one should interpret the results from the equation only as a gross indication of average technological trends in fighter aircraft development, remembering that other factors can also influence the time at which a particular level of technology becomes available.[11]

This index was developed only for fighters. Consequently, this approach was tested only with the fighter subsample.

Program/Construction Characteristics

The developers of the previous RAND airframe cost model concluded: "It may be time for a change in direction. . . . [The] use of a parametric model implies a belief that all programs will have neither more nor less than their share of problems, yet we know that some programs are plagued with problems that are not a function of aircraft characteristics. It might be productive to examine the influence of what might be called program characteristics on program cost."[12]

Following this recommendation, we investigated several program variables, including the maximum tooling capability, currency of contractor experience with similar airframes, engine status (new or "off-the-shelf" engine), degree of weapon system integration (emphasis on sophisticated fire control systems and missiles rather than guns), and the type of development program (prototype or concurrent). This study in no way represents an exhaustive examination of the program variables, however. We were unable to consider such things as the effect of schedule on cost, the financial condition of the contractor, local economic conditions, and possible complementarities among the various development and production processes.

Additionally, as a result of suggestions by individuals within the aircraft industry, we investigated several variables related primarily to airframe construction, including the design ultimate load factor, wing type, structural efficiency, internal density, and carrier capability.

[11]Ref. 17, p. 27.

[12]See Ref. 3, p. 53.

REPORT ORGANIZATION

Section II describes the study data elements—the aircraft in the estimating sample, the cost categories for which estimating relationships are being developed, and the potential explanatory variables. Section III provides an overview of how the cost data and aircraft characteristics vary by mission type and over time. Section IV summarizes the general approach, including a discussion of the variable combinations selected for analysis and the statistical methods employed. Sections V, VI, VII, and VIII present results of the analyses of the full estimating sample, the fighter subsample, the bomber/transport subsample, and the attack aircraft subsample, respectively. Section IX summarizes the main findings of the study and suggests possible future courses of action.

Appendix A contains cost-element definitions and cost/airframe unit weight plots, and Appendix B contains explanatory variable definitions and values. Appendix C summarizes the most recent set of RAND-developed airframe CERs (DAPCA-III). Finally, Appendix D provides typical cost-quantity slopes and labor costs that are suggested for use with the recommended set of CERs.

II. DATA ELEMENTS

ESTIMATING SAMPLE

The full estimating sample consists of the following 34 "new-design" aircraft:[1]

Model	First Flight Date	Model	First Flight Date[2]
A-3	1953	F-4	1961
A-4	1954	F-14	1970
A-5	1958	F-15	1972
A-6	1960	F-16	1976
A-7	1965	F-18	1978
A-10	1974	F-86	1948
B-52	1954	F-89	1950
B-58	1957	F-100	1953
B/RB-66	1954	F-101	1954
C-5	1968	F-102	1955
C-130	1955	F-104	1956
C-133	1956	F-105	1956
KC-135	1957	F-106	1956
C-141	1963	F-111	1967
F3D	1950	S-3	1972
F3H	1955	T-38	1959
F4D	1954	T-39	1960

Approximately two-thirds of the aircraft in the sample first flew prior to 1960, and roughly half first flew prior to 1957 (i.e., more than 30 years ago).

[1]The classification of an aircraft as new or derivative is not an entirely objective procedure. For example, although the F-102A program laid the groundwork for the F-106A, the F-106A is classified as a new design in the database because, in contrast to the F-102A, it had a new engine, relocated air intakes, variable-geometry air inlets, a modified vertical stabilizer, and markedly better performance (Ref. 17, p. 14).

[2]The first flight dates presented in this report reflect the first flight date of the version that was most representative of the aircraft that was to become operational. These dates thus reflect the first flight date of the developmental aircraft, not earlier experimental or prototype aircraft. Thus, although the F-4A aircraft first flew in May 1958, the first flight date of the F-4B aircraft is presented. Similarly, even though the YF-17, the antecedent of the F-18, first flew in May 1974, the first flight date of the F-18A aircraft is presented.

The attack subsample consists of the aircraft with mission code A plus the S-3.[3] The fighter subsample encompasses all mission code F aircraft. The bomber/transport subsample consists of aircraft with mission codes B and C plus the KC-135. The two trainer aircraft (the T-38 and T-39) are not included in any subsample.

DEPENDENT VARIABLES

Costs are dealt with at both the total program level[4] and at the major cost-element level (engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control).[5] Generally, estimating at the total program level is best suited to long-range planning studies where little detail is required. The major-cost-element approach, on the other hand, is best suited to situations where some insight into why a program is going to cost a certain amount is required, or where informed adjustments need to be made based on special aircraft characteristics. Despite these differences in typical applications, however, past RAND analyses (as well as this one) have shown that the two approaches are essentially equivalent in terms of their accuracy.

Costs are not examined in terms of nonrecurring and recurring because for the older aircraft in the sample, original records were not kept in this way, and any such separation at this time would be arbitrary.[6]

Engineering, tooling, manufacturing labor, and quality control are estimated in terms of man-hours rather than dollars, for two reasons: (1) it avoids having to make adjustments for annual price changes, and (2) it permits comparison of real differences in labor requirements.[7] Manufacturing material, development support, and flight test do not

[3]Some question may be raised concerning the inclusion of the S-3 in the attack subsample. However, in terms of weight, speed, climb rate, and ultimate load factor, it is within the range of the mission code A aircraft. Furthermore, it has the capability to be used in an attack (for torpedos and depth bombs), possessing a relatively steep maximum dive angle. Because of these features, its inclusion in the attack sample was felt appropriate.

[4]Total program costs are "normalized" values and not the actual reported dollar amounts, i.e., the dollar amounts for engineering, tooling, manufacturing labor, and quality control have been determined by applying fully burdened, industry-average labor rates to the hours reported for each category.

[5]Cost-element definitions are provided in Appendix A.

[6]Ref. 3, p. 8.

[7]The major limitation of the man-hours approach is that it does not account for differences in overhead rates. Consequently, differences in such things as capital/labor ratios cannot be addressed.

lend themselves to this approach and were therefore estimated in dollars.

EXPLANATORY VARIABLES

During the formulation stage of this study, many characteristics were considered as potential explanatory variables. However, to be among the characteristics that were considered for inclusion in the CERs (Table 2), a variable had to meet the following requirements:

1. It had to be logically related to cost, that is, a rationale had to be constructed that would explain why cost should be influenced by the variable.[8]
2. It had to be "readily available" in the early stages of aircraft conceptualization.
3. It had to have an available historical record.[9]

The rationales for considering or not considering suggested explanatory variables are explained below. Variable definitions are provided in Appendix B.

Size

Weight and *wetted area* are logical variables to be tested for significance because they are indexes of size, and, all other things being equal, a large airframe should cost more than a smaller one. *Airframe unit weight* consists primarily of structural items and, of all weight measures, would seem to most closely represent what the airframe manufacturer is directly responsible for designing and producing. *Empty weight* includes not only the structure but also the engines and mission equipment and thus would also seem to capture what the airframe manufacturer is responsible for integrating and installing.

[8]This requirement is intended to be a middle ground between two extremes. One extreme would require the development of an in-depth, step-by-step explanation of why a particular characteristic should affect cost, prior to any statistical analysis. This approach would require following a typical airframe from drawing board to final assembly, showing how the characteristic of interest impacts cost at each "step" along the way. The other extreme would not require any a priori rationale but would use statistical analysis to establish explanatory variables and then be concerned with developing the rationale. Our approach required the establishment of an intuitive rationale for each potential explanatory variable prior to any statistical analysis, which was then used as a tool for final variable selection.

[9]In the context of this study, an available record was one that was currently available within RAND. External data collection for this study was extremely limited.

Table 2

POTENTIAL EXPLANATORY VARIABLES[a]

Variable	All Aircraft	Fighter	Attack	Bomber/ Transport
Size				
Airframe unit weight (AUW)	X	X	X	X
Empty weight (EW)	X	X	X	X
Wetted area	X	X	X	X
Technical/performance factors				
Maximum speed	X	X	X	X
Speed class	X	X	X	X
Specific power		X		
Maximum specific energy		X		
Climb rate	X	X	X	X
Maximum sustained load factor		X		
Thrust-to-weight ratio		X		
Breguet range factor		X		
Useful load fraction	X	X	X	X
Predicted first flight date (technology index)		X		
Predicted first flight date (composite performance)		X		
Construction				
Design ultimate load factor	X	X	X	X
Structural efficiency factor		X		
Carrier capability designator	X	X	X	X
Engine location designator	X	X	X	X
Wing type	X	X	X	X
Ratio of wing area to wetted area	X	X	X	X
Ratio of (EW-AUW)/AUW	X	X	X	X
Ratio of avionics weight to AUW	X	X	X	X
Number of black boxes	X	X	X	X
Program				
Number of test aircraft	X	X	X	X
Maximum tooling capability	X	X	X	X
New engine designator	X	X	X	X
Contractor experience designator	X	X	X	X
Weapon system designator		X		
Program type designator	X	X	X	X

[a]Blanks indicate that not all explanatory variables are applicable to all aircraft samples. In some instances, certain characteristics are not meaningful for certain aircraft types, e.g., specific power is not particularly relevant when describing bomber/transport aircraft. In other cases, the effort required to collect or calculate the appropriate values was beyond the scope of this study. For example, the Breguet range factor was readily available only for fighter aircraft, and calculating it for the other aircraft types would have been a major undertaking.

Gross weight and *combat weight* were not tested because they include items (e.g., ordnance, fuel, crew) which, while clearly considered during the development stage, are not within the airframe manufacturer's responsibility for design, fabrication, or installation. The connection between cost and gross weight/combat weight would thus be less strong than that between cost and airframe unit weight/empty weight. Other size variables such as *wingspan* and *fuselage length* were not considered because, individually, they are not representative of the entire airframe.

Technical/Performance Factors

Generally speaking, improvements in performance capability (speed, acceleration, maneuverability, range/payload, etc.) are associated with greater airframe complexity. For example, as *speed* approaches Mach 1, the effects of compressibility necessitate more sophisticated aerodynamic and structural design (e.g., swept wings); as speed increases beyond Mach 1, wings generally become thinner; as speed approaches Mach 2, more complex variable-cross-section engine air inlets are normally used for efficient operation; and at Mach 2.5, materials such as titanium are needed, since the strength of aluminum alloys decreases at the elevated temperatures encountered at higher speeds. Speed alone, however, ignores the problems associated with packaging high speed in a small, lightweight airframe. Consequently, *specific power* (fighters only) is the chosen parameter, because it normalizes for size.

Maximum specific energy (fighters only), an important parameter in energy-maneuverability theory, collectively describes the speed and altitude performance of fighter aircraft. The sea-level *rate of climb* indicates the specific excess power an aircraft has available to climb or change velocity and hence provides a measure of acceleration capability.

The *maximum sustained load factor* (fighters only) and the *thrust-to-weight ratio* (fighters only) were selected to characterize aircraft maneuverability. Generally speaking, increased maneuverability is associated with increased airframe "strength."

Differences in the range/payload capability are reflected in the *Breguet range factor* (fighters only) and useful load fraction. The range factor measures how well fuel energy is translated into range by the airframe's aerodynamics as well as the propulsion system. The *useful load fraction* provides a gross measure of an aircraft's ability to carry fuel and payload.

The *predicted first flight date* (fighters only) is viewed, first, as an indicator of the technological sophistication of the airframe, and second, as a composite performance variable. As an indicator of technological sophistication, it complements other performance variables, and as a composite performance variable, it substitutes for other performance variables. However, in either case, the impact on cost should be the same: higher levels of technological sophistication or performance should result in higher cost.[10]

The *lift-to-drag ratio* was not considered, since no hypothesis explaining a logical relation to cost could be developed. However, it does significantly influence range and is incorporated into the Breguet range factor. *Ceiling* was not considered, because the vast majority of aircraft in the sample are capable of altitudes in excess of 40,000 ft, and further differences are usually attributable to the engine rather than the airframe.

Construction

This group of explanatory variables is used to account for differences in how airframes are constructed. The *design ultimate load factor* (the maximum load factor to which the airframe is designed) can be viewed as a measure of airframe "strength." The *structural efficiency factor* (fighters only), defined as the ratio of structural weight to the product of the design ultimate load factor and stress design weight, is used to quantify differences in materials and design/fabrication technology. Presumably, improvements in materials and design/fabrication techniques should produce lower structural efficiency factors. Since they are more difficult to achieve, lower structural efficiency factors should result in higher costs than higher structural efficiency factors.

The *carrier-capability designator* is intended to separate aircraft designed for carrier operation (i.e., those having catapult takeoff, arresting-gear landing, wing fold, and additional corrosion problems) from those that are not. The *engine location designator* indicates whether an aircraft's engines are embedded in the fuselage or located in nacelles under the wing. It is felt that the process of designing and integrating an engine into a fuselage (e.g., tailoring the inlet airflow, routing cables and hydraulic lines around the engine) is more difficult than that of placing the engine in a nacelle under the wing.

The next two variables deal with wing construction. *Wing type* reflects the perceived complexity of alternative wing configurations—straight, swept, delta, and variable sweep. The *ratio of wing area to wetted area* is used to account for the observation that wing structure is

[10]Since the predicted first flight date and actual first flight date are highly correlated by construction (i.e., they are essentially equivalent), the possibility exists that when the predicted first flight date is entered into a cost equation it might actually be capturing a time trend that is unrelated to technology (e.g., changes in procurement policy).

normally less expensive per pound than fuselage or empennage structure.[11] Consequently, everything else being equal, aircraft with larger ratios of wing area to wetted area should be less expensive than aircraft with smaller ratios.

The two weight ratios—*empty weight minus airframe unit weight to airframe unit weight [(EW-AUW)/AUW]* and *avionics weight to airframe unit weight [AV/AUW]*—are used to account for the difficulty of integrating and installing nonstructural items within the airframe. Weights are used as proxies for volume, since volumes could not be obtained. Empty weight less airframe unit weight accounts for the weight of the engine(s) and mission equipment, while avionics weight is limited to the electronics group.

Like the ratio of avionics weight to airframe unit weight, the *number of black boxes* also attempts to account for the difficulty of integrating and installing electronics into an airframe. However, it does not capture the relative difficulty of packaging particularly well, especially when applied to a sample containing both large and small aircraft. A black box is loosely defined as an electronic component or unit (usually with an identifiable AN designation[12] or manufacturer part number) which provides a communication, navigation, identification, fire control, electronic countermeasures (ECM), or data processing function. Excluded are instruments, electromechanical components, intercoms, emergency transmitters, chaff dispensers, cameras, and electronics located in pods. Differences in the level of technology embodied in black boxes are not accounted for, nor is the fact that the level of black box aggregation varies from aircraft to aircraft. For example, a centralized aircraft and weapon control unit (such as the MG-10 on the F-102) may subsume several functions identified separately on other aircraft. Furthermore, since an aircraft's avionics suite is constantly changing, even during initial production runs, it is very difficult to select a "representative" suite. This analysis has used the suite appearing on the first production version of the aircraft as a basis for determining the number of black boxes. The numbers of black boxes by aircraft and by date of first flight are shown in Table 3, which also shows an apparent pre-1960/post-1960 break in the quantity of black boxes for the attack, transport, and fighter mission types.

An additional half-dozen or so construction-related variables were not considered, for a variety of reasons. *Wing loading* and *aspect ratio* were not considered because reasonable hypotheses relating them to

[11] See Ref. 18.

[12] An AN (Army-Navy) designation indicates that an electronic item has been classified in accordance with the Joint Electronics Type Designation System.

Table 3

NUMBERS OF BLACK BOXES

Aircraft	Year of First Flight	Numbers of Black Boxes
Attack Aircraft		
A-3	1953	8
A-4	1954	6
A-5	1958	13
A-6	1960	23
A-7	1965	19
S-3	1972	33
A-10	1974	14
Bomber/Transport Aircraft		
B-52	1954	24
B/RB-66	1954	--
B-58	1957	26
C-130	1955	17
C-133	1956	16
KC-135	1957	16
C-141	1963	26
C-5	1968	27
Fighter Aircraft		
F-86	1948	4
F3D	1950	9
F-89	1950	9
F-100	1953	5
F4D	1954	9
F-101	1954	9
F3H	1955	6
F-102	1955	9
F-104	1956	6
F-105	1956	11
F-106	1956	12
F-4	1961	14
F-111	1967	18
F-14	1970	21
F-15	1972	24
F-16	1976	--
F-18	1978	--
Other Aircraft		
T-38	1959	7
T-39	1960	10

cost could not be developed. *Wing taper,*[13] the *ratio of wing thickness to wing chord,*[14] *maximum dynamic pressure in the flight envelope,* and *part count* were not considered because historical values for these variables were not readily available. Furthermore, part count was not felt to be a variable for which a value could be accurately estimated in the concept-formulation stage. The *maximum lift coefficient*[15] in combat configuration was not considered because efforts to measure this parameter uniformly were stymied by inconsistent definitions among aircraft of what constitutes the maximum usable lift coefficient condition (e.g., inconsistent definitions of controllability under various conditions of buffet). The maximum lift coefficient in a landing or takeoff configuration was investigated indirectly through the use of a variable that distinguishes between land-based aircraft and carrier-capable aircraft; the latter generally place greater emphasis on developing high lift at low speed.

Finally, even though we know that *airframe materials* utilization varies significantly from aircraft to aircraft (see Table 4), the development of a meaningful materials index was beyond the scope of this study. Such an index would require, for each aircraft, not only the material distribution (e.g., aluminum, titanium, steel, composite) and form (sheet, plate, forging), but also the relative finished part costs at the time the aircraft was manufactured. Furthermore, the required data are readily available for only a few of the most recent aircraft.[16]

Program

Unlike the first three groupings of explanatory variables which dealt with the physical characteristics of airframes, the final group of variables deals with the management decisions associated with airframe programs. An increased *number of test aircraft* suggests an expanded flight-test program with increased engineering planning, instrumentation, fuel, maintenance, and data requirements, and a resultant increase in cost. *Maximum tooling capability* is used to capture the effect on cost of the production rate (e.g., greater specialization of

[13]Higher wing-taper ratios generally mean more unique parts (e.g., ribs).

[14]Lower thickness-to-chord ratios reflect relatively thinner, wider wings which are more difficult to construct than thicker, narrower wings.

[15]Higher maximum lift coefficients are normally associated with more complex wing leading- and trailing-edge devices, the cost of which presumably increases the cost of the overall wing.

[16]For additional discussion of material indexes, see Ref. 19, pp. 189–202.

Table 4

AIRFRAME MATERIALS UTILIZATION

(Percentage of airframe structure weight)[a]

	Aircraft[b]						
Material	F-4 (1961)	F-111 (1967)	F-14 (1970)	F-15 (1972)	B-1A (1974)	F-16 (1976)	F-18 (1978)
Aluminum	70	59	48	52	52	79	48
Titanium	9	5	29	40	20	2	14
Steel	16	33	22	5	14	4	15
Composites	5	1	1	2	4	5	11
Other		2	—	1	10	10	12

[a]Structure weight includes the following weight groups: wing, tail, body, alighting gear, and engine section (see MIL-STD-1374, *Weight and Balance Data Reporting Forms for Aircraft*, September 30, 1977).

[b]First flight dates shown in parentheses.

labor, reduced material costs through increased volume purchase) and the physical volume of tooling (initial and duplicate sets).

The *"new engine" designator* distinguishes those airframes that are mated with a new engine (excluding growth versions) from those that are not. A new engine is expected to experience more difficulties than an "off-the-shelf" or growth engine, and these difficulties should also be reflected in the airframe development (e.g., in schedule slippage, airframe modifications). The derivation of the "new engine" designator is provided in Table 5. Clearly, some interpretation was required. For example, during the early and mid-1950s, when aircraft were developed at a rapid pace, engines were occasionally introduced virtually simultaneously on more than one aircraft. Some cases were truly joint applications (e.g., the J79 for the B-58 and F-104). In other near-simultaneous cases, such as the J57, we used subjective judgment in determining which aircraft bore the brunt of engine development.

The *contractor experience designator* is intended to deal with the notion that a contractor with recent experience on a specific mission-type aircraft should be more efficient, both in development and production, than a contractor without that experience.[17] The problem, of

[17]An alternative approach would focus not on the individual contractor's recent experience, but rather on the experience of the airframe industry as a whole with a given type of aircraft design. In other words, only "first-of-a-kind" designs would be designated "no experience." The problem with this approach is that almost every aircraft is the first "something." (For example, see Ref. 17, p. 7, Table 1, "Milestones in U.S. Jet Fighter Development.")

Table 5

NEW ENGINE DESIGNATOR

Aircraft	Initial Engine on Production Aircraft	Initial Aircraft Application(s) of Engine	First Application?
A-3	J57	B-52/F4D	No
A-4	J65	B-57	No
A-5	J79	B-58/F-104	No
A-6	J52	A-6	Yes
A-7	TF30[a]	F-111	No
A-10	TF34	S-3	No
B-52	J57	B-52/F4D	Yes
B-58	J79	B-58/F-104	Yes
B/RB-66	J71	B/RB-66/F3H	Yes
C-5	TF39	C-5	Yes
C-130	T56	C-130	Yes
C-133	T34	C-133	Yes
KC-135	J57	B-52/F4D	No
C-141	TF33	B-52H/707	No
F3D	J34	F6U/F2H	No
F3H	J71[b]	B/RB-66/F3H	Yes
F4D	J57	B-52/F4D	Yes
F-4	J79	B-58/F-104	No
F-14	TF30	F-111	No
F-15	F100	F-15	Yes
F-16	F100	F-15	No
F-18	F404	F-18	Yes
F-86	J47	B-45/F-86	Yes
F-89	J35	F-84/FJ-1	No
F-100	J57	B-52/F4D	No
F-101	J57	B-52/F4D	No
F-102	J57	B-52/F4D	No
F-104	J79	B-58/F-104	Yes
F-105	J75	F-105	Yes
F-106	J75	F-105	No
F-111	TF30	F-111	Yes
S-3	TF34	S-3	Yes
T-38	J85	T-2C	No
T-39	J60	T-39/C-140	Yes

[a]Without afterburner.

[b]F3H switched from J40 to J71 at the fifty-seventh production unit.

course, comes in defining experience. The question of what constitutes an "experienced nucleus" of engineers and production workers is beyond the scope of this study. The answer to this question would involve, for example, questions of:

1. Relevancy:
   - Does a company-sponsored effort constitute experience in the same sense as a government-sponsored effort?
   - Does a program that does not reach production provide experience in the same sense as one that does?
   - Does experience with aircraft types other than the current aircraft type benefit the current program? (e.g., Does recent experience with attack aircraft help fighter development? Does recent experience with commercial transport aircraft help military transport aircraft development?)
2. Currency: How recent is the experience?
3. Definition of nucleus: quantity, quality, and mix of labor types.
4. Labor mobility, both intracompany and intercompany.

Consequently, for this study, contractor experience is arbitarily defined in the following way: A company that receives a government-sponsored mission-type-X development contract (excluding contract definition phases) prior to the conclusion of another government-sponsored mission-type-X production program is said to have experience. Furthermore, for all but cargo aircraft, an additional condition of experience is that the propulsion types of the current and prior aircraft also be the same. That is, the applications of propeller and jet propulsion to combat aircraft are considered sufficiently dissimilar that credit for experience is not given if the prior case involved a different type of propulsion system. The derivation of the contractor experience designator is provided in Table 6. Note that in cases where there is a definite similarity between an aircraft and an antecedent, credit for experience is given irrespective of the mission designations (e.g., A-3 and B/RB-66, F-8 and A-7).

This definition obviously has limitations. For example, changes in avionics technology and basing mode (e.g., land vs. carrier) are ignored, as is relevant subcontractor experience.[18] However, additional sophisti-

[18]For example, to "obtain" relevant "carrier" experience for the S-3 program, Lockheed teamed with LTV, which at the time was still producing the A-7. In fact, by the time the last S-3 was completed, LTV was producing about 53 percent of the airframe unit weight.

Table 6

CONTRACTOR EXPERIENCE DESIGNATOR

Aircraft	Contractor	Start Date of Govt.-Sponsored Research	Prior Aircraft of Same Mission Type Produced by Contractor and Approximate Date Production Concluded	Experience?
A-3	Douglas	Mar 1949	A-1 (prop)/Feb 1957	No
A-4	Douglas	Jun 1952	A-3/1960	Yes
A-5	North American	Jun 1956	A-2 (prop)/Mar 1954	No
A-6	Grumman	Mar 1959	S-2 (prop)/1967(?)	No
A-7	LTV	Mar 1964	F-8[a]/Sep 1964	Yes
A-10	Fairchild	Dec 1970	None identified	No
B-52	Boeing	Jul 1948	B-47/Feb 1957	Yes
B-58	Convair	Feb 1951	B-36 (prop)[b]/Aug 1954	No
B/RB-66	Douglas	Jan 1953	A-3[c]/1960	Yes
C-5	Lockheed	Oct 1965	C-141/Jul 1968	Yes
C-130	Lockheed	Jul 1951	None identified	No
C-133	Douglas	Feb 1953	C-124 (prop)/May 1955	Yes
KC-135	Boeing	Aug 1954[d]	KC-97 (prop)/Jul 1956	Yes
C-141	Lockheed	Apr 1961	C-130 (prop)/current	Yes
F3D	Douglas	Apr 1946	P-70 (prop)/1943(?)	No
F3H	McDonnell	Sep 1949	F2H/Oct 1953	Yes
F4D	Douglas	Dec 1948	F3D/Oct 1953	Yes
F-4	McDonnell	Oct 1954	F3H/Nov 1959	Yes
F-14	Grumman	Jan 1969	F-111/Feb 1969[e]	Yes
F-15	McDonnell	Dec 1969	F-4/current	Yes
F-16	General Dynamics	Apr 1972	F-111/August 1969	No
F-18	McDonnell	Apr 1972	F-15/current	Yes
F-86	North American	May 1945	FJ-1/1957	Yes
F-89	Northrop	Jun 1946	P-61 (prop)/1946	No
F-100	North American	Jan 1952	F-86/Dec 1956	Yes
F-101	McDonnell	Jan 1952	F2H/Oct 1953	Yes
F-102	Convair	Sep 1951	None identified[f]No	
F-104	Lockheed	Mar 1953	F-94/May 1954	Yes
F-105	Republic	Sep 1952	F-84/Aug 1957	Yes
F-106	Convair	Nov 1955	F-102/Apr 1958	Yes
F-111	General Dynamics	Nov 1962	F-106/Jan 1961	No
S-3	Lockheed	Aug 1969	P-3 (prop)/current	No[g]
T-38	Northrop	Nov 1958	None identified	No
T-39	North American	Mar 1956	T-28 (prop)/1956	Yes[h]

[a]The A-7 evolved from the F-8.

[b]Only two YB-60s (a B-36 derivative using eight J57 jet engines) were produced by Convair.

[c]The B/RB-66 evolved from the A-3.

[d]The "Dash 80" jet transport started in May 1952 with corporate funds.

[e]The F-111B was formally canceled in July 1968; the last F-111B acceptance was in February 1969. Grumman funding on the F-111 was $150 million in 1969 and $68 million in 1970.

[f]The XF-92 was less than a full-scale prototype.

[g]The P-3 is a relatively large, land-based, propeller-driven aircraft, while the S-3 is a relatively small, carrier-based, jet aircraft.

[h]Additionally, the T-2 was developed and produced approximately concurrently with the T-39.

cation in the definition of contractor experience would require increased subjectivity on the part of the analyst.[19]

The intent of the *weapon system designator* (fighters only) is to identify those aircraft whose development placed more emphasis on air-to-air missiles and sophisticated fire-control systems than on gun armament.[20]

Aircraft identified as "weapon systems" were considered to be relatively more expensive in terms of design integration and equipment installation than aircraft identified as "gun platforms." The most difficult aircraft to classify were the F-101 and the F-104. The F-101A carried four 20mm M-39 cannons, twelve spin-stabilized rockets, and three AIM-4A Falcon missiles. But it was not until the B version of the F-101 that the cannon armament was deleted and the MG-13 fire control system was added. The dominant emphasis of the original F-104 program was flight performance. Armament for the F-104A consisted of a 20mm M-61 Vulcan rotary cannon and two infrared-homing Sidewinder missiles, but no search radar. The F-104C added provisions for two additional Sidewinders.

The final variable considered was the *type of development program*. The ultimate effect of the prototype concept on total cost (i.e., cost through the end of production) has been the subject of considerable debate (see Ref. 21). Prototype developments typically emphasize the early demonstration of technical feasibility, before a commitment is made to large-scale production for inventory. The initial stages of such developments are usually characterized by little or no production planning and limited tooling. They are "change amenable," i.e., even though some commitment may have been made to production, it is not so total as to preclude change at or close to the start of production. For this analysis, a prototype program is arbitrarily defined as one in which the first lot consists of three or fewer aircraft (see Table 7).

There are three other program variables which were not considered for a variety of reasons—the number of test articles (other than flight-test vehicles), data requirements, and the number of concurrent contractor programs. The *number of test articles* was not considered because almost invariably, regardless of the technological advance, one fatigue article and one static article are built and tested. Consequently, there would not be sufficient variation in the variable to make it worth considering. *Data requirements* are frequently mentioned as a contrib-

[19]In reality, the relevant issue is much broader than implied here and encompasses questions of management strength, facility availability, financial condition, etc. The more generalized topic of "contractor capability" is discussed in Chap. 13 of Ref. 20.

[20]This definition attempts only to distinguish between two possible emphases and does not exclude fighters that have both missile and gun armament.

Table 7

PROGRAM-TYPE DESIGNATOR

Aircraft	Number of Aircraft in First Lot	Program-Type Designator (1 = concurrent) (2 = prototype)	Aircraft	Number of Aircraft in First Lot	Program-Type Designator (1 = concurrent) (2 = prototype)
A-3	2	2	F-4	7	1
A-4	1	2	F-14	6	1
A-5	11	1	F-15	20	1
A-6	8	1	F-16	2	2
A-7	7	1	F-18	2	2[d]
A-10	2	2	F-86	3	2
B-52	2	2	F-89	2	2
B-58	13	1	F-100	2	2
B/RB-66	5	1	F-101[a]	31	1
C-5	5	1	F-102[b]	42	1
C-130	2	2	F-104	2	2
C-133	12	1	F-105	15	1
KC-135	1	1	F-106	35	1
C-141	5	1	F-111	18	1
F3D	3	2	S-3	8	1
F3H	2	2	T-38	2	2
F4D	2	2	T-39[c]	94	2

[a]The XF-88 program (2 prototypes) evolved into the F-101 program. However, the XF-88 was not considered a direct antecedent of the F-101 because different engines were used, there were substantial differences in the planform, and the empty weight of the F-101 was twice that of the XF-88.

[b]The XF-92 program evolved into the F-102 program. However, like the XF-88/F-101 case, the XF-92 is not considered a direct antecedent of the F-102 because different engines were used, the planforms were substantially different (the F-102 utilized area-rule), and the empty weight of the F-102 was twice that of the XF-92.

[c]Prior to government funding, a single T-39 prototype was developed as a private venture.

[d]The F-18 program (11 FSD aircraft) evolved from the YF-17 program (2 prototypes).

utor to high costs. Unfortunately, little discussion has been devoted to what the proper metric should be: The number of unique reporting requirements? The number of manual pages that must be scripted? The volume of cost/performance reports generated? In any case, regardless of the metric, historical data for this type of variable are not readily available. A lack of readily available historical data was also the reason for not testing the effect of the *number of concurrent contractor programs* on cost. It was felt that a greater number of concurrent programs (including commercial efforts) would increase the demand for labor and material, and would thereby result in cost increases. On the other hand, if engineers are in short supply, engineering might be limited to that which was absolutely necessary, which would result in cost decreases. But if the same type of logic is applied to the manufacturing aspect, skilled labor would be spread thinner, which would have adverse implications for both cost and quality. Another potentially significant effect would be on overhead rates. Presumably, overhead rates will fall as the number of concurrent programs (i.e., the business base) increases.

III. DATA OVERVIEW

This section provides a brief overview of the database on which our inferences about airframe costs are based, to enable the reader to better assess the quality and applicability of the results. It summarizes the characteristics of the full 34-aircraft estimating sample, compares characteristics by mission subsample, and concludes with a comparison of pre-1960 and post-1960 characteristics.

FULL ESTIMATING SAMPLE

Aircraft Characteristics

Values for the size, performance, construction, and program characteristics for each aircraft in the full estimating sample are given in Tables 8a, 8b, and 8c. These data lead to the following observations:

1. Minimum and maximum values for airframe unit weight, empty weight, wetted area, speed, and climb rate each span a range of more than an order of magnitude.
2. Several of the continuous variables have maximum values that fall substantially beyond two standard deviations: airframe unit weight, empty weight, wetted area, speed, climb rate, number of black boxes, number of test aircraft, and maximum tooling capability.
3. Based on any of the three size measures, the C-5 is approximately twice as large as the next largest aircraft in the sample.
4. The sample does not include any aircraft that are both relatively large and relatively fast (such as the B-1A would have been, with an airframe unit weight of approximately 150,000 lb and a speed of Mach 2). This point is illustrated in Fig. 2.

There are, of course, differences among the aircraft which are not accounted for in Tables 8a, b, and c. Some of the differences relate to the way the program is managed, but in any case, it is difficult to find an aircraft without at least one unique aspect. The differences listed below are indicative of the types that are difficult to account for in a generalized parametric model:

Table 8a

AIRCRAFT CHARACTERISTIC VALUES: SIZE AND TECHNICAL/PERFORMANCE

	Size			Technical/Performance			
Aircraft	Airframe Unit Weight (lb)	Empty Weight (lb)	Wetted Area (ft^2)	Maximum Speed (kn)	Speed Class	Climb Rate (ft/min)	Useful Load Fraction
A-3	23,931	35,999	3,899	546	1	5,050	.485
A-4	5,072	9,146	1,144	565	1	8,400	.594
A-5	23,499	32,714	2,950	1147	3	27,900	.439
A-6	17,150	25,298	2,100	561	1	10,000	.583
A-7	11,621	15,497	1,690	595	1	8,580	.578
A-1	14,842	19,856	2,463	389	1	5,100	.559
B-5	112,672	177,816	16,650	551	1	5,120	.605
B-5	32,686	55,560	5,450	1147	3	17,830	.659
B/RB-66	30,496	42,549	4,372	548	1	5,000	.487
C-5	279,145	320,085	30,800	495	1	5,160	.555
C-130	43,446	58,107	7,590	326	1	3,900	.532
C-133	96,312	114,690	13,150	304	1	3,400	.617
KC-135	70,253	97,030	10,770	527	1	5,900	.677
C-141	104,322	136,900	14,100	491	1	7,270	.579
F3D	10,136	14,860	1,843	470	1	4,100	.484
F3H	13,898	21,270	1,908	622	1	13,000	.455
F4D	8,737	16,050	1,500	628	1	20,200	.427
F-4	17,220	27,530	2,150	1222	3	40,600	.508
F-14	26,500	36,825	3,155	(a)	(a)	(a)	(a)
F-15	17,550	26,795	2,646	(a)	(a)	(a)	.499
F-16	9,565	14,062	1,390	(a)	2	(a)	.574
F-18	16,300	20,583	(b)	(a)	2	(b)	.439
F-86	6,788	10,040	1,070	590	1	7,650	.416
F-89	18,119	23,870	(b)	546	1	11,800	.347
F-100	12,118	18,260	1,509	752	2	25,700	.371
F-101	13,423	24,720	2,060	872	2	29,600	.493
F-102	12,304	19,460	2,170	680	2	18,700	.374
F-104	7,963	11,570	1,078	1150	3	51,500	.508
F-105	19,301	24,500	1,998	1112	3	38,300	.538
F-106	14,620	23,180	2,230	1153	3	34,500	.363
F-111	33,150	46,170	2,580	1262	3	12,600	.533
S-3	18,536	26,581	2,607	429	1	5,000	.494
T-38	5,376	7,410	(b)	699	2	28,500	.387
T-39	7,027	9,753	(b)	468	1	4,270	.477
Mean	33,943	46,021	4,967	754	..	19,100	.503
Std. dev.	51,429	61,703	6,398	321	..	17,216	.086
Range	5,072-279,145	7,410-320,085	1,070-30,800	304-1250+	..	3,400-50,000+	.347-.677

[a]Classified.
[b]Not available.

Table 8b

AIRCRAFT CHARACTERISTIC VALUES: CONSTRUCTION

Aircraft	Design Ultimate Load Factor	Carrier Capability Designator	Engine Location Designator	Wing Type[a]	Ratio of Wing Area to Wetted Area	Ratio of (EW-AUW) to AUW	Ratio of Avionics Weight to AUW	No. of Black Boxes
A-3	5.00	2	2	2	.200	.50	.085	8
A-4	10.50	2	1	2	.227	.80	.084	6
A-5	11.00	2	1	2	.237	.39	.110	13
A-6	9.75	2	1	2	.251	.48	.170	23
A-7	10.50	2	1	2	.222	.33	.059	19
A-10	4.93	1	2	1	.205	.34	.041	14
B-52	3.00	1	2	2	.240	.58	.070	24
B-58	3.00	1	2	3	.283	.70	(c)	26
B/RB-66	4.80	1	2	2	.178	.40	.092	(c)
C-5	3.75	1	2	2	.201	.15	.017	27
C-130	3.75	1	2	1	.230	.34	.085	17
C-133	3.75	1	2	1	.203	.19	.021	16
KC-135	3.75	1	2	2	.225	.38	(c)	16
C-141	3.75	1	2	2	.228	.31	.023	26
F3D	9.00	2	1	1	.218	.47	.145	9
F3H	11.25	2	1	2	.272	.53	.060	6
F4D	9.50	2	1	3	.371	.84	.215	9
F-4	12.75	2	1	2	.247	.60	.101	14
F-14	(c)	2	1	4	.179	.39	.112	21
F-15	11.00	1	1	2	.230	.53	.090	24
F-16	(c)	1	1	2	.216	.47	(c)	(c)
F-18	(c)	2	1	2	(c)	.26	(c)	(c)
F-86	11.00	1	1	2	.269	.48	.106	4
F-89	8.50	1	1	1	(c)	.32	(c)	9
F-100	11.00	1	1	2	.255	.51	.016	5
F-101	11.00	1	1	2	.179	.84	.075	9
F-102	10.50	1	1	3	.305	.58	.164	9
F-104	11.00	1	1	2	.182	.45	.076	6
F-105	13.00	1	1	2	.193	.27	.074	11
F-106	10.50	1	1	3	.312	.59	.190	11
F-111	11.00	1	1	4	.203	.39	.081	18
S-3	5.25	2	2	2	.229	.44	.220	33
T-38	11.00	1	1	2	(c)	.38	(c)	7
T-39	11.00	1	2	2	(c)	.39	(c)	10
Mean	8.57	—	—	—	.233	.46	.094	15
Std. dev.	3.40	—	—	—	.044	.17	.068	8
Range	3.00–13.00+	—	—	—	.178–.371	.15–.84	.016–.220	4–33

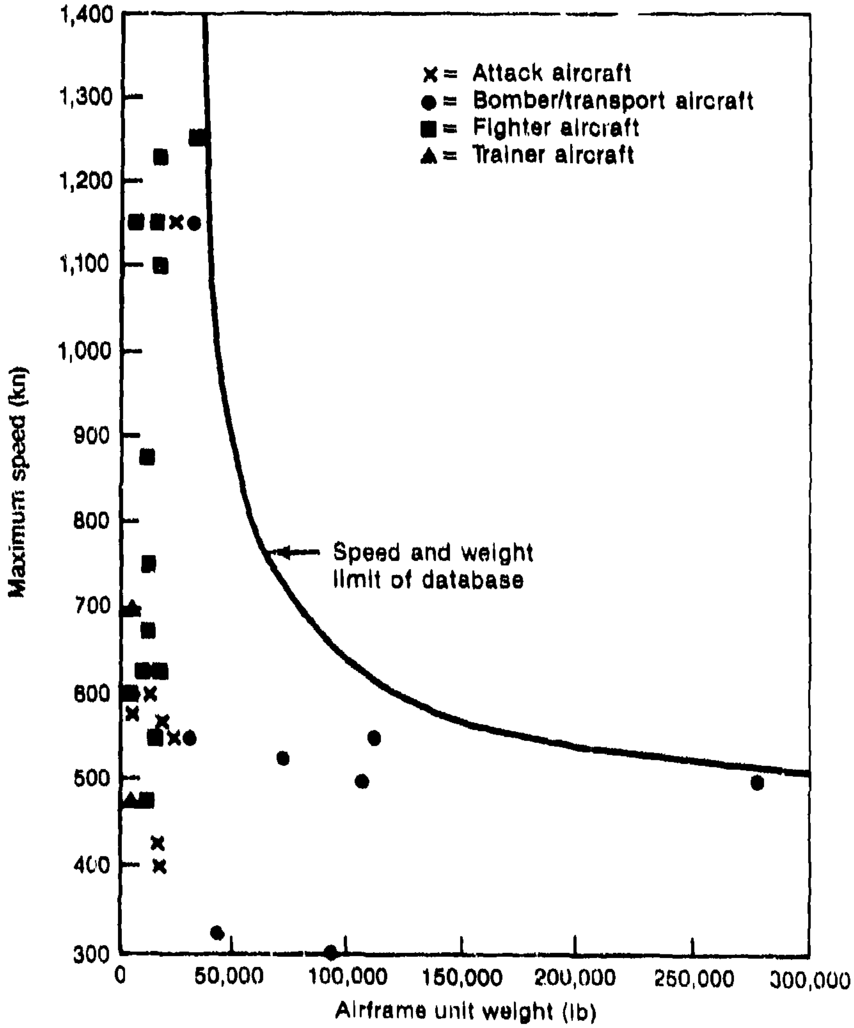
[a]1 = straight; 2 = swept; 3 = delta; 4 = variable sweep.
[b]Classified.
[c]Not available.

Table 8c

AIRCRAFT CHARACTERISTIC VALUES: PROGRAM

Aircraft	No. of Test Aircraft	Maximum Tooling Capability	New Engine Designator	Contractor Experience Designator	Program Type Designator
A-3	5	8	1	2	2
A-4	9	40	1	1	2
A-5	11	6	1	2	1
A-6	8	8	2	2	1
A-7	7	24	1	1	1
A-10	8	15	1	2	2
B-52	13	10	2	1	2
B-58	30	8	2	2	1
B/RB-66	14	10	2	1	1
C-5	10	2	2	1	1
C-130	9	18	2	2	2
C-133	10	2	2	1	1
KC-135	8	15	1	1	2
C-141	5	9	1	1	1
F3D	13	20	1	2	2
F3H	18	13	2	1	2
F4D	13	20	2	1	2
F-4	7	15	1	1	1
F-14	12	8	1	1	1
F-15	20	12	2	1	1
F-16	10	(a)	1	2	2
F-18	13	(a)	2	1	2
F-86	12	30	2	1	2
F-89	6	25	1	2	2
F-100	13	50	1	1	2
F-101	17	20	1	1	1
F-102	31	45	1	2	1
F-104	19	20	2	1	2
F-105	15	17	2	1	1
F-106	26	29	1	1	1
F-111	18	21	2	2	1
S-3	8	5	2	2	1
T-38	14	24	1	2	2
T-39	4	5	2	1	2
Mean	13	17	...	...	...
Std. dev.	7	12	...	...	...
Range	4-31	2-50	...	...	...

[a]Not available.



NOTE: The F-14, F-15, F-16, and F-18 are not shown, but all four lie within the envelope.

Fig. 2—Speed versus weight of aircraft

1. The C-130 and C-133 are turboprop aircraft, while all other sample aircraft utilize turbojet or turbofan engines.
2. The KC-135 was designed and produced more or less concurrently with the commercial 707 model.
3. The B/RB-66 was produced concurrently with the A-3, the aircraft from which it evolved.
4. The F-102 did not meet its speed performance specifications until after a major redesign.
5. The F-106 and A-7 were outgrowths of the F-102 and F-8 programs, respectively.
6. The F-111 was the first aircraft for which common Air Force/Navy usage was made a requirement at inception.
7. The B-58's utilization of honeycomb skin panels represented a major state-of-the-art advance.
8. The C-5 program utilized the acquisition concepts of total package procurement and concurrent development and production.
9. The A-10 program utilized competitive prototyping and design-to-cost acquisition concepts.

Cost Data

The cost data used in this study were obtained from both government and industry sources. As stated previously, data plots for each of the major cost elements (engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, and quality control), as well as total program cost, are provided in Appendix A.[1] The relative importance of each cost category is shown in Table 9 as a function of production quantity. As one might expect, the labor, material, and quality-control elements become increasingly important as quantity increases, while engineering, tooling, development support, and flight test become less important. Clearly, other things being equal, one would want the estimating relationships derived for the two manufacturing categories to be the most accurate because of the relatively large contribution of these categories to program cost.

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[1]In previous RAND reports on airframe cost estimation (Refs. 1, 2, and 3), proprietary restrictions *prevented the inclusion of any cost information whatsoever.* However, for this update, we felt that it was valuable to be able to visually establish relationships among the observations. Consequently, we obtained permission from the manufacturers to provide the cost data in graphical format. We were not given permission to present the data in tabular format, nor did we request such permission.

Table 9

COST-ELEMENT DISTRIBUTION, BY PRODUCTION QUANTITY[a]

	Quantity							
	25		50		100		200	
Element	\$/lb[b]	%	\$/lb[b]	%	\$/lb[b]	%	\$/lb[b]	%
Engineering	229	25	131	22	74	19	42	15
Tooling	173	19	104	18	62	16	36	13
Manufacturing labor	230	25	176	30	135	34	103	38
Manufacturing material	87	9	74	12	63	16	55	20
Development support	86	9	43	7	22	5	11	4
Flight test	93	10	47	8	23	6	12	5
Quality control	25	3	19	3	16	4	12	5
Total	923	100	594	100	395	100	271	100

[a]Averages for full estimating sample (34 aircraft).
[b]Cumulative average costs (in thousands of 1977 dollars) per pound of airframe unit weight.

MISSION SUBSAMPLES

Aircraft Characteristics

Table 10 provides an indication of how aircraft characteristics vary with mission type. As one would expect, the fighter and attack aircraft are roughly comparable in size; the bombers and transports are much larger. In terms of combat engagement characteristics (speed, climb rate, and design ultimate load factor), the ordering (from low to high) is bomber/transport, attack, and fighter; for payload capability (useful load fraction) the order is reversed. In terms of the two packaging ratios (ratio of [EW-AUW] to AUW and ratio of avionics weight to AUW), the attack and fighter aircraft are essentially equivalent, while the bomber/transport aircraft are significantly lower. On the other hand, the bomber/transports have, on average, substantially more black boxes than do either the attack or fighter aircraft. Finally, planned production rates for attack and fighter aircraft are, on average, roughly twice those of bomber/transport aircraft.

Cost Data

Airframe costs per pound, by mission type, are shown in Table 11. As one might expect, the relatively light, fast fighters are the most expensive per pound, while the large, relatively slow bombers and transports are the least expensive. The data also indicate that, on

Table 10

SUMMARY OF AIRCRAFT CHARACTERISTIC VALUES, BY MISSION TYPE

	Attack Aircraft (7 observations)		Bombers and Transports (8 observations)		Fighters (17 observations)	
Explanatory Variable	Mean	Range	Mean	Range	Mean	Range
Size						
Airframe unit weight, lb	16,379	5,072–23,931	96,167	30,496–27,9145	15,158	6,788–33,150
Empty weight, lb	23,584	9,146–35,999	125,342	42,549–320,085	22,338	10,040–46,170
Wetted area, sq ft	2,408	1,144–3,899	12,860	4,372–30,800	1,952	1,070–3,155
Performance						
Maximum speed, kn	605	389–1,147	549	304–1,147	932	470–1,250+
Climb rate, ft/min	10,004	5,000–27,900	6,698	3,400–17,830	29,622	4,100–50,000+
Useful load fraction	.533	.439–.594	.589	.487–.677	.459	.347–.574
Construction						
Design ultimate load factor, g's	8.13	4.93–11.00	3.69	3.00–4.80	10.89	8.50–13.50
Ratio of (EW-AUW) to AUW	.47	.34–.80	.38	.15–.70	.50	.26–.84
Ratio of avionics weight to AUW	.110	.041–.220	.043	.017–.092	.107	.016–.215
Number of black boxes	17	6–33	22	16–27	11	4–24
Program						
Number of test aircraft	8	5–11	12	5–30	15	6–31
Maximum tooling capability	15	6–40	9	2–18	22	8–50

Table 11

AIRFRAME COSTS, BY MISSION TYPE[a]

Element	Fighter Subsample	Bomber/ Transport Subsample	Attack Aircraft Subsample
Number of observations	17	8	7
Average airframe unit weight, lb	15,158	96,167	16,379
Average speed, kn	932	549	605
Cost distribution, \$/lb[b] (%)			
Engineering	149 (21)	43 (16)	114 (22)
Tooling	104 (15)	46 (17)	70 (13)
Manufacturing labor	219 (31)	100 (37)	185 (36)
Manufacturing material	94 (13)	51 (19)	74 (14)
Development support	56 (8)	9 (3)	26 (5)
Flight test	59 (8)	10 (4)	28 (6)
Quality control	29 (4)	11 (4)	22 (4)
Total	710 (100)	270 (100)	519 (100)

[a]Averages for individual subsamples.
[b]Cumulative average costs (in thousands of 1977 dollars) per pound of airframe unit weight at a quantity of 100.

average, the fighter and attack programs tend to put relatively more emphasis on the development phase (engineering, development support, and flight test) than do bomber/transport programs and relatively less on the manufacturing phase (tooling, labor, and material).

CHANGES OVER TIME

As will be discussed in Secs. V and VI, in our analyses of both the full estimating sample and the fighter subsample, we noted that several of the derived equations tended to underestimate the costs of the most recent sample aircraft. We believe this is a result of the *combined* effects of numerous design-related and institutional changes that have occurred over the 1948–1978 time period (e.g., the increased emphasis on electronics, along with changes in materials of construction, manufacturing processes, and the regulatory framework). We originally planned to develop specific measures that would reflect these changes, but this approach did not prove to be as successful as we had hoped it would be. For many of the more abstract concepts, we could not develop unambiguous measures. And even where relatively unambiguous measures could be developed and tested, the results were mar-

Table 12

AIRFRAME COSTS, BY TIME PERIOD[a]

Element	Full Estimating Sample			Fighter Subsample		Bomber/Transport Subsample		Attack Aircraft Subsample	
	Pre-1960	Post-1960	Post-1960 less C-5 & C-141	Pre-1960	Post-1960	Pre-1960	Post-1960	Pre-1960	Post-1960
Number of observations	21	13	11	11	8	6	2	3	4
Average airframe unit weight, lb	27,674	44,071	17,223	12,492	20,048	64,310	191,734	17,500	15,537
Average speed, kn	711	823	883	779	1,212	567[c]	493	753[d]	494
Costs, $/lb[b]									
Engineering	62	87	183	91	215	46	39	86	138
Tooling	76	48	90	100	108	65	28	85	57
Manufacturing labor	149	121	204	209	230	118	80	211	161
Manufacturing material	55	71	106	64	127	48	54	79	70
Development support	21	23	58	41	74	14	5	18	34
Flight test	27	20	55	47	73	18	3	34	24
Quality control	17	14	29	25	34	14	7	24	21
Total	407	384	725	577	861	323	216	537	505

[a]Average values for stated samples.
[b]Cumulative average costs (in thousands of 1977 dollars) per pound of airframe unit weight at quantity of 100.
[c]451 kn if B-58 (1,147 kn) is excluded.
[d]556 kn if A-5 (1,147 kn) is excluded.

ginal at best. Consequently, two alternative approaches were investigated:

1. Deletion of older, less relevant aircraft from the sample.
2. Incorporation of a time variable (date of first flight) into the equations that exhibited the underestimation problem.

In trying the first approach, we deleted all aircraft from the sample with first flight dates prior to 1960. To provide some limited insight into the types of changes that have occurred, aircraft cost and weight/speed characteristics for the pre-1960 and post-1960 time periods are compared in Table 12.[2]

At first glance, it appears that average program costs actually decreased (from $407/lb to $384/lb). However, closer examination reveals that this conclusion is driven by two very large transport aircraft, the C-141 and the C-5 (for a given quantity of aircraft, the C-141 and C-5 account for roughly two-thirds of the total post-1960 airframe unit weight produced). Excluding these two aircraft results in a 78 percent increase in per pound costs. Further analysis of the individual subsamples suggests that the increased costs are largely attributable to fighters, which increased in both average speed and average size by roughly 60 percent. The fighter and attack aircraft data also suggest increased emphasis on engineering and development support, and the fighter data show considerably higher costs for manufacturing materials and development support.

[2]The choice of 1960 as a breakpoint does not imply a hard-and-fast distinction between the pre-1960 and post-1960 aircraft. Rather, it represents a balance between deleting older, potentially less relevant observations and attempting to maintain an acceptable sample size.

IV. APPROACH

Potential explanatory variables have been divided into four general categories—size, performance, construction, and program (see Table 2). Ideally, an airframe cost estimating relationship would incorporate at least one variable from each category, but from a practical standpoint, concern about collinearity among the size and performance explanatory variables led to a limit of one explanatory variable that could be incorporated into an estimating relationship from any single category.[1] Thus, there could be as many as four variables per equation, but no more than four. For a relatively large sample, such as the all-mission dataset that has 34 observations, the possibility of four variables per equation does not cause any concern (for a sample size of 34, the resulting equation would still have 29 degrees of freedom with which to estimate the error term). On the other hand, for very small samples, such as the bomber/transport subsample (8 observations) and the attack aircraft subsample (7 observations), the possible incorporation of four independent variables does not seem to be particularly prudent (the resulting equations would have only 3 and 2 degrees of freedom, respectively, with which to estimate the error term). Therefore, we tentatively limited the potential number of explanatory variables for these two subsamples to two. Then, in order to stay between the extremes, the number of explanatory variables per equation for the fighter subsample (17 observations) was tentatively limited to three. These limits are summarized in the following table:

Sample	Number of Observations	Limit on Number of Explanatory Variables/CER[2]
All mission types	34	4
Fighter aircraft	17	3
Bomber/transport aircraft	8	2
Attack aircraft	7	2

[1]Strictly speaking, concerns about collinearity in the size and performance categories should not limit the number of explanatory variables considered in the construction and program variable categories. However, the limit was extended to these other two categories to keep the analytical effort within reasonable bounds. Even so, as the subsequent analysis will show, the possibility of more than one construction variable or one program variable per equation is a moot point: It was difficult to identify acceptable equations incorporating even one construction variable or one program variable.

[2]This is not to suggest that these limits are "absolute" maximums—they are not. They simply reflect our judgment regarding an appropriate balance between sample size and the potential number of explanatory variables.

Given these limitations, the question then became one of which combinations of categories to consider. To the best of our knowledge, all airframe manufacturers use some measure of size (usually weight) as their basic scaling dimension in developing cost estimates, although other factors frequently do enter in. Consequently, it does not seem unreasonable for us to assume that a size variable must appear in all equations.[3] Given this additional restriction, the specific variable combinations we examined for each sample are shown in Table 13.

An additional complication arose from the fact that we were not developing a single CER, but a *set* of CERs. Normally, the development of a representative set of CERs would require selecting the "best" equation for each cost element. However, past experience indicates that the resulting equation set would contain different size and performance variables (e.g., the engineering CER might utilize airframe unit weight/speed, while the tooling CER uses empty weight/climb rate). This would give the analyst the unenviable task of trying to explain why one size/performance variable combination predicts cost more

Table 13

VARIABLE COMBINATIONS EXAMINED[a]

Variable Combination Group[b]	Sample: Full Estimating Sample (Max. = 4)	Fighter Sample (Max. = 3)	Bomber/ Transport Sample (Max. = 2)	Attack Aircraft Sample (Max. = 2)
1. Combinations incorporating size and performance variables only	S S/P	S S/P	S S/P	S S/P
2. Combinations that additionally incorporate construction/program variables	S/P/C S/P/PG S/P/C/PG	S/P/C S/P/PG S/C S/PG	S/C S/PG	S/C S/PG
3. Combinations that additionally incorporate fighter technology index	--	S/P/TI	--	--

[a]S = size; P = performance; C = construction; PG = program; TI = fighter technology index.

[b]The reason for these groupings is explained in the accompanying text.

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[3]Except for the flight-test cost element, for which the mandatory variable was the number of test aircraft.

accurately for one cost element while another combination predicts cost more accurately for another cost element. Furthermore, variable interaction (e.g., interaction between speed and rate of climb) would make the user's input task more difficult. On the other hand, such mixing of size and performance variables could in fact be the preferred solution. Consequently, where applicable, two types of equation sets have been developed: one that maintains the integrity of the set size and performance variables and one that utilizes the "best" equation for each cost element regardless of the size or performance variables.

The first step in addressing the three study premises delineated in Sec. I was to identify, by sample, all potentially useful estimating relationships for each cost element resulting from the variable combinations listed above. For this first step, "potentially useful" included only those estimating relationships in which all equation variables were significant at the 5 percent level. Each equation satisfying this initial screening criterion was then scrutinized in accordance with a set of evaluation criteria dealing with statistical quality, reasonableness of results, and predictive capability (described below).

At this point, we addressed the marginal benefit of adding a construction/program variable or an objective technology index to the estimating relationships. This was done by comparing the estimating relationships in variable combination groups 2 and 3 (see Table 13) against the corresponding "baseline" estimating relationships in group 1. Assuming that everything else was roughly comparable, the primary measure used to assess the benefit was the improvement in the standard error of estimate when the construction/program variable or technology index was incorporated.

The next step was to develop, for each sample, the two types of alternative equation sets discussed previously. For the first type, this consisted of selecting the "best" estimating relationship for each of the "most promising" size/performance combinations for each cost element. For the second type, it consisted of selecting the single "best" estimating relationship for each cost element. Generally speaking, we tried to select estimating relationships that satisfied the following objectives:

- Each variable is significant at the 5 percent level.
- Variables taken collectively are significant at the 5 percent level.
- Credible results are produced.
- There are no unusual residual patterns.
- The standard error of estimate is minimized.

We next selected a "recommended" set for each sample. This selection was based primarily on a comparison of the individual equation standard errors of estimate and how well (in terms of relative deviation) the sets as a whole estimated the costs of a subsample of four recent aircraft.

Finally, the "recommended" sets of estimating relationships for each *mission sample* were compared to the "recommended" set for the *total aircraft sample* to address the issue of sample homogeneity.

Multiple-regression analysis was used to examine the relationship between cost and the explanatory variables. Because of time restrictions, we tested only one equation form—logarithmic linear. The linear model was rejected because its main analytic property, constant returns to scale, does not correspond with real-world expectations. Of the two remaining equation forms considered (logarithmic and exponential), the logarithmic form seemed most appropriate for the cost estimation process, since it minimizes relative errors rather than absolute errors. Also, a prior RAND study that examined the logarithmic and exponential forms in the context of airframe CERs concluded that "the logarithmic model form appears more realistic than the exponential form on both prior judgment and subsequent analysis of the residuals."[4]

Cost-element categories that are a function of quantity were examined at a quantity of 100. Developing the estimating relationship at a given quantity rather than using quantity as an independent variable in the regression analysis (as was done in Ref. 2) has the following advantages:

- It provides an extra degree of freedom.
- It avoids potential serial correlation problems.
- It avoids unequal representation of aircraft (caused by unequal numbers of lots).

EVALUATION CRITERIA

The estimating relationships obtained in this analysis were evaluated on the basis of their statistical quality,[5] intuitive reasonableness, and predictive properties.

[4]Ref. 22, p. 30.

[5]Statistics are based on the logarithmic form of the equation.

Statistical Quality

Even with the limitations placed on possible variable combinations in this study, the potential number of estimating relationships is still substantial. The numbers for the engineering cost element alone for each sample are shown below:

Total sample	387
Fighter sample	456
Bomber/transport sample	45
Attack sample	45

To reduce the number of estimating relationships requiring closer scrutiny, we used variable significance as an initial screening device—in general, only equations for which all variables were significant at the 5 percent level (based on a one-sided t-test) were presented in our sample results (reported in the companion Notes). Occasionally, however, this criterion was relaxed so that a useful comparison could be provided or so that the requirement for integrity of set size and performance variables could be fulfilled.

The following statistical measures and checks were also utilized in the evaluation process and are presented in the companion Notes:

- The coefficient of determination (R^2) was used to indicate the percentage of variation explained by the regression equation.
- The standard error of estimate (SEE) was used to indicate the degree of variation of data about the regression equation. It is given in logarithmic form but may be converted into a percentage of the corresponding hour or dollar value by performing the following calculations:

  (a) $e^{+SEE} - 1$

  (b) $e^{-SEE} - 1$

  For example, a logarithmic standard error of 0.18 yields standard error percentages of +20 and −16 of the corresponding hour or dollar value.
- The F-distribution was used to determine collectively whether the explanatory variables being evaluated affect cost. Generally speaking, those equations for which the probability of the null hypothesis was greater than 0.05 were avoided when selecting representative equation sets.
- We checked for potential multicollinearity problems by determining the correlation of each independent variable in an

estimating relationship with all other independent variables in that relationship. Generally, we avoided estimating relationships with intercorrelations greater than 0.8.

- Plots of equation residuals were given cursory examinations for unusual patterns. In particular, plots of residuals versus predictions (log/log) were checked to make sure that the error term was normally distributed with zero mean and constant variance. Additionally, plots of residuals versus time (log/linear) were examined to see whether or not the most recent airframe programs were overestimated or underestimated Generally speaking, estimating relationships with patterns were not considered for use in representative equation sets.
- "Cook's Distance" was utilized to identify influential observations in the least-squares estimates.[6] It combines individual measures of residual magnitude and "location" within the factor space to produce a measure of the overall impact any single point has on the least-squares solution. For purposes of this analysis, an influential observation was one which, if deleted from the regression, would move the least-squares estimate past the edge of the 10 percent confidence region for the equation coefficients. When an observation was consistently identified as influential, it was reassessed in terms of its relevance to the sample in question. If a reasonable and uniform justification for its exclusion could be developed, the observation was deleted from the sample and the regressions were rerun (in fact, this occurred only when the B-58 was deleted from the bomber/transport sample). Otherwise, the influential observation was simply flagged to alert potential users to the fact that its deletion from the regression sample would result in a significant change in the equation coefficients.

Reasonableness

Variable coefficients used in airframe CERs should both provide credible results and conform whenever possible to the normal estimating procedures employed by the airframe industry. Thus, an estimating relationship with a variable coefficient sign that was not consistent with a priori notions (see Table 14) was not considered for inclusion in a representative equation set.

We also paid close attention to the magnitude of variable coefficients to ensure that realistic results were obtained from all equations.

[6]See Ref. 23.

Table 14

A PRIORI NOTIONS REGARDING EFFECT OF INCREASE IN EXPLANATORY VARIABLE ON COST ELEMENT

Explanatory Variable	Engr.	Tooling	Mfg. Labor	Mfg. Material	Dev. Support	Flight Test	Quality Control	Total Program
Size								
Airframe unit weight (AUW)	+	+	+	+	+	+	+	+
Empty weight (EW)	+	+	+	+	+	+	+	+
Wetted area	+	+	+	+	+	+	+	+
Technical/performance factors								
Maximum speed	+	+	+	+	+	+	+	+
Speed class	+	+	+	+	+	+	+	+
Specific power	+	+	+	+	+	+	+	+
Maximum specific energy	+	+	+	+	+	+	+	+
Climb rate	+	+	+	+	+	+	+	+
Maximum sustained load factor	+	+	+	+	+	+	+	+
Thrust-to-weight ratio	+	+	+	+	+	+	+	+
Breguet range factor	+	+	+	+				+
Useful load fraction	+	+	+	+				+
Predicted first flight date (technology index)	+		–[h]	+	+	+		+
Predicted first flight date (composite performance)	+	+	+	+	+	+	+	+
Construction								
Design ultimate load factor	+		+	+	+			+
Structural efficiency factor[b]	–		–	–	–			–
Carrier capability designator[c]	+		+	+	+	+		+
Engine location designator[d]	–	?	–	+				?
Wing type designator[e]	+	+	+		+	+		+
Ratio of wing area to wetted area		–	–					–
Ratio of (EW-AUW)/AUW	+		+	+	+	+	+	+
Ratio of avionics weight to AUW	+		+	+	+	+	+	+
Number of black boxes	+		+	+	+	+	+	+
Program								
Number of test aircraft						+		
Maximum tooling capability		+	–					?
New engine designator[f]	+					+		?
Contractor experience designator[f]	+	+	+	+	+	+	+	+
Weapon system designator[c]	+	+	+	+	+	+	+	+
Program type designator[g]	?[i]	?[i]			?[i]	?[i]		[illegible]

NOTE: A plus indicates a positive effect; a minus, a negative effect. An effect that was thought to be negligible is indicated by a blank, and an uncertain effect is indicated by a question mark.

[a]Speed class: 1 = less than Mach .95; 2 = Mach .95 to Mach 1.94; 3 = Mach 1.95 to Mach 2.5; 4 = greater than Mach 2.5.

[b]Low values are more difficult to achieve.

[c]No = 1; yes = 2.

[d]Engine location: embedded in fuselage = 1; in nacelles under wing = 2.

[e]Wing types: 1 = straight; 2 = swept; 3 = delta; 4 = variable sweep.

[f]Yes = 1; no = 2.

[g]Concurrent = 1; prototype = 2

[h]Over time, major assembly labor hours have tended to decrease because of improvements in manufacturing methods (e.g., unitized design), while fabrication labor hours have tended to increase because of the introduction of titanium and composite materials. The net effect has been a decrease in manufacturing hours.

[i]It is not known whether total cost (including both prototype effort and full scale development) for prototype programs is greater or less than that for concurrent programs.

This applied to coefficients that appeared to be too small as well as to those that appeared to be too large. The situation is especially critical with respect to dummy variables (e.g., the contractor experience designator), where the answers are most often given in terms of all or nothing. While most determinations of this kind are subjective, there was one application that was relatively objective. Traditionally, size variables provide returns to scale in the production-oriented cost elements (tooling, labor, material, and total program cost)—that is, increases in airframe size are accompanied by less-than-proportionate increases in cost.[7] If the opposite phenomenon is observed, it is generally believed to be the result of failing to adequately control for differences in construction, materials, complexity, and/or other miscellaneous production factors. Consequently, we generally tried to avoid estimating relationships containing variables with exponents that we felt were either too large or too small (that is, exponents that placed either too much or too little emphasis on the parameter in question). But even more restrictively, for the production-oriented cost elements, no estimating relationship possessing a size variable exponent greater than one was considered for a representative equation set.

Predictive Properties

Confidence in the ability of an equation to accurately estimate the acquisition cost of a future aircraft depends largely on how well the acquisition costs of the most recent aircraft in the database are estimated. Normally, statistical quality and predictive quality are viewed as one and the same. Unfortunately, when dealing with airframe costs, this is not always the case, because our knowledge of what drives airframe costs is limited and because the sample sizes we are dealing with are relatively small and not evenly distributed with respect to first flight date (see Fig. 3).[8] Consequently, we also evaluated the estimating relationships on the basis of how well they estimated costs for a subset of the most recent aircraft in the database.

An equation's predictive capability can usually be seen by excluding a few of the most recent aircraft from the regression and then observing how well (in terms of the relative deviation) the resultant equation estimates the costs of the excluded aircraft. However, in this case, the

[7]This concept dates back to the early 1940s and the so-called ARCO factor (which took its name from the World War II Aircraft Resources Control Office).

[8]Only aircraft in the RAND airframe cost database are reflected in this figure. First flights of modification aircraft, aircraft that never entered production (e.g., the F-107), and recent aircraft for which a production quantity of 100 has not yet been reached (e.g., the B-1B) are specifically excluded.

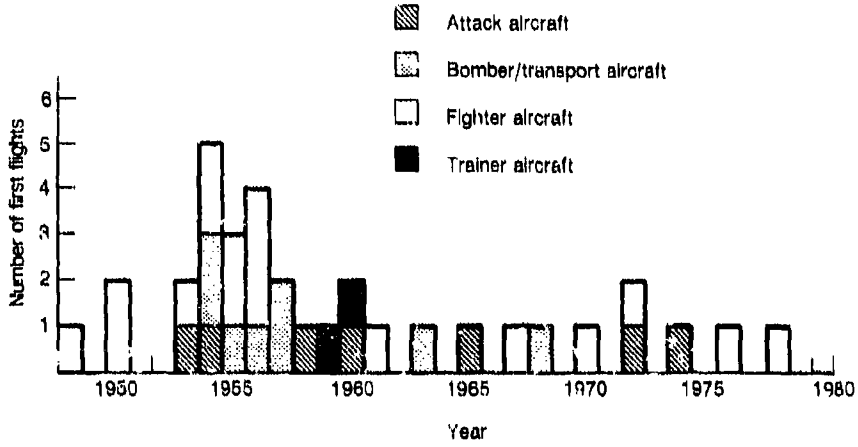

Fig. 3—Number of first flight events, 1948–1978

small sample sizes preclude this option. Consequently, the measure of predictive capability used in this analysis was the relative deviation for a subset of recent sample aircraft. The relative deviations were determined on the basis of the predictive form of the equation, not the logarithmic form used in the regression.[9]

SUPPORTING DOCUMENTATION

The companion Notes (see Preface) provide sufficient information to enable users to make their own judgments concerning the appropriateness of the "recommended" set. The Notes contain:

- Plots of cost versus airframe unit weight for each cost element.
- Summary tables, by cost element, of all estimating relationships meeting our initial screening criterion (each variable significant

[9] If cost is estimated in a log-linear form such as

$$\ln COST = \beta_0 + \beta_1 \ln WEIGHT + \beta_2 \ln SPEED + \ln \epsilon ,$$

the expected cost is given by

$$COST = \left(e^{\beta_0}\ WEIGHT^{\beta_1}\ SPEED^{\beta_2}\right) \times e^{\sigma^2/2} ,$$

where σ^2 is the actual variance of ϵ in the log-linear equation. Since the actual variance is not known, the standard error of estimate can be used as an approximation (see Ref. 22, p. 44).

> at the 5 percent level). Additional information includes the F-ratio, coefficient of determination, standard error of estimate, number of observations, intercorrelation thresholds, identification of residual patterns and influential observations, and comments on the reasonableness of results (sign and magnitude of variable coefficients).

The presentation of all equations meeting our initial screening criterion serves two purposes. First, it enhances understanding of the factors that affect airframe costs (e.g., those characteristics that are significant in the context of the variable combinations investigated). Second, it provides alternatives that may be better suited to a particular situation than the recommended set. Clearly, the selection of a "recommended" set for each sample is by nature subjective. Consequently, our "recommended" sets should be viewed only as possible solutions. All relevant results should be reviewed before a course of action is selected.

V. FULL ESTIMATING SAMPLE RESULTS

RECOMMENDED SET OF CERs

Generally, for each of the airframe cost categories, we were able to identify at least a half-dozen potentially useful estimating equations. Nevertheless, we selected one set of equations, which we considered to be the most representative and applicable to the widest range of estimating situations.[1] This set, which utilizes empty weight and speed as the basic size/performance variable combination, is presented in Table 15.

The estimating relationships in Table 15 are based on a subsample of only 13 aircraft. We chose not to use the full sample because observations made during the course of the analysis raised questions concerning the applicability of some of the older aircraft in the sample to aircraft of the future. More specifically, the engineering, manufacturing material, development support, flight-test, and total program CERs tended to underestimate the costs of the most recent aircraft. An additional analysis of post-1960 aircraft indicated that this subsample would be a better guide to the future.

The estimating relationships in the recommended equation set vary significantly in statistical quality. Four of them have standard errors of estimate of about 0.30, while the other three have standard errors of estimate of about 0.50 or greater. None of the equations meets our standard-error-of-estimate goal of 0.18.[2] On the other hand, the lowest standard errors of estimate in the set are associated with cost elements (tooling, labor, and material) that typically account for 66 percent of total program cost at a quantity of 100; at a quantity of 200, these elements account for 71 percent. Finally, despite the sample stratification, there is still some tendency for the engineering, development support, and total program cost equations to underestimate the costs of the most recent sample aircraft.

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[1] The complete analysis of the full estimating sample is provided in Note N-2283/1-AF, *Aircraft Airframe Cost Estimating Relationships: All Mission Types*.

[2] A value of 0.18 (roughly ±20 percent) as a goal may seem high. However, past RAND experience (see Refs. 1, 2, and 3) indicates that the derivation of an airframe CER with this low a standard error of estimate would be quite an accomplishment.

Table 15

SET OF AIRFRAME CERs BASED ON SAMPLE OF 13 POST-1960 AIRCRAFT

Equation	R^2	SEE	F	N
CERs for Individual Cost Elements				
$ENGR_{100} = .0103\ EW^{.777}_{(.001)}\ SP^{.894}_{(.011)}$	.72	.55	13	13
$TOOL_{100} = .0201\ EW^{.777}_{(.000)}\ SP^{.696}_{(.000)}$	.92	.25	56	13
$LABR_{100} = .141\ EW^{.820}_{(.000)}\ SP^{.484}_{(.013)}$	.88	.31	38	13
$MATL_{100} = .241\ EW^{.921}_{(.000)}\ SP^{.621}_{(.003)}$	.91	.30	51	13
$DS = .0251\ EW^{.630}_{(.016)}\ SP^{1.30}_{(.012)}$	.54	.82	6	13
$FT = .687\ EW^{.525}_{(.032)}\ SP^{.622}_{(.037)}\ TESTAC^{1.21}_{(.010)}$	.83	.48	15	13
$QC_{100} = .076 \times LABR_{100}$ if cargo	—	—	—	2
$= .133 \times LABR_{100}$ if noncargo	—	—	—	11
CER for Total Program Cost				
$PROG_{100} = 2.57\ EW^{.798}_{(.000)}\ SP^{.738}_{(.003)}$	.85	.36	29	13

NOTE: Airframe costs may be estimated at the major cost-element level or, alternatively, directly at the program level.

R^2 = coefficient of determination; SEE = standard error of estimate (logarithm); F = F-statistic; N = sample size. Numbers in parentheses are significance levels of individual variables. Notation in equations is defined in the list of Acronyms and Abbreviations (p. xiii).

Suggested cost-quantity slopes and labor rates to be used in conjunction with this set are provided in Appendix D.

CONSTRUCTION/PROGRAM VARIABLES

Our attempts to incorporate construction and program characteristics were not successful. Although variables characterizing the equipment placed within the airframe structure and contractors' relevant experience were frequently found to be statistically significant, they did not, as a rule, result in any substantial improvement in the quality of the equations. In most cases, the equations incorporating such variables did not produce results that we viewed as credible. Moreover, even in those few instances where the equations did produce credible results, the reduction in the standard error of estimate was never more than two or three percentage points.

COMPARISON WITH DAPCA-III RESULTS

Overall, the statistical quality of the set of airframe CERs presented here is not much different from that of the previous set of RAND-developed airframe CERs (DAPCA-III).[3] A comparison of the standard errors of estimate of the two sets (Table 16) yields mixed results: Those of the current set are lower for the tooling, labor, and material cost elements, but higher for engineering, development support, and flight test. Furthermore, there is little difference in the accuracy with which the two sets project the costs of the subsample of 13 post-1960 aircraft (see Table 17). However, since only two of the current equation-set estimates fall short of the corresponding DAPCA-III estimates (see Table 18), and the shortfalls are both small, it is not unreasonable to suggest that the current equation set will produce estimates that are greater than or equal to those produced by DAPCA-III.

Table 16

COMPARISON OF STANDARD ERRORS OF ESTIMATE: DAPCA-III AND CURRENT RECOMMENDED SET

	Standard Error of Estimate (log)	
Cost Element	DAPCA-III	Current
Engineering	0.26	0.56
Tooling	0.41	0.26
Manufacturing labor	0.34	0.31
Manufacturing material	0.36	0.30
Development support	0.72[a] 0.66[b]	0.82
Flight test	0.44	0.48
Total program	0.27	0.36

[a]Labor component of development support.
[b]Material component of development support.

[3]The DAPCA-III estimating relationships are given in Appendix C.

Table 17

RELATIVE ACCURACY OF ESTIMATES OBTAINED USING DAPCA-III AND CURRENT EQUATION SETS

(Percent by which actual cost exceeds (+) or falls short of (−) estimated cost)

	Sum of Elements		Total Program CER	
Aircraft	DAPCA-III	Current	DAPCA-III	Current
A-6	+11	0	+10	+ 0
A-7	−81	−86	−86	−85
A-10	+15	+13	+17	+15
C-5	+12	+ 4	+14	+ 5
C-141	−43	−64	−46	−67
F-4	+ 7	−14	+ 2	−16
F-111	+17	+ 2	+16	+ 7
F-14	− 7	−22	−11	−20
F-15	+ 9	−15	+ 6	− 5
F-16	− 8	−23	−13	−20
F-18	+36	+33	+34	+36
T-39	−36	−37	−40	−39
S-3	+44	+39	+45	+40
Average of absolute values	25	27	26	27
Number underestimated (+)	8	5	8	5
Number overestimated (−)	5	7	5	7

Table 18

COMPARISON OF ESTIMATES OBTAINED USING DAPCA-III AND CURRENT EQUATION SETS

	Characteristics			Percent by Which Current Set Estimate Exceeds (+) or Falls Short of (−) DAPCA-III Estimate	
Aircraft	Airframe Unit Weight (lb)	Empty Weight (lb)	Speed (kn)	Sum of Elements	Total Program (CER)
A-6	17,150	25,298	561	+13	+11
A-7	11,621	15,497	595	+ 2	0
A-10	14,842	19,856	389	+ 2	+ 1
C-5	279,145	320,085	495	+ 9	+10
C-141	104,322	136,900	491	+15	+15
F-4	17,220	27,530	1,222	+23	+18
F-111	33,150	46,170	1,262	+17	+11
F-14	26,500	36,825	1,000+*	+14	+ 4
F-15	17,550	26,795	1,000+*	+26	+14
F-16	9,565	14,062	1,000+*	+14	+ 6
F-18	16,300	20,583	1,000+*	+ 5	− 3
T-39	7,027	9,753	468	+ 1	− 1
S-3	18,536	26,581	429	+10	+ 9

*Actual value is classified.

INCORPORATION OF A TIME VARIABLE

As stated previously, the engineering, manufacturing material, development support, flight-test, and total program CERs for the full sample tended to underestimate those costs for the most recent sample aircraft. Our preferred response was to limit the sample to post-1960 aircraft. However, another approach is possible: the incorporation of a time variable into those equations that exhibit a pattern of underestimation. Our analysis of this option is described below.

The use of a cumulative time variable in a CER is not a new idea (e.g., see Refs. 3 and 4). Such measures are typically utilized when it is not otherwise possible to characterize the changes in cost that have occurred over time. A time variable invariably captures the *combined* effect of shifts in many diverse factors, including the regulatory framework, aircraft "quality" (factors not directly related to speed such as maneuvering capability, the materials of construction, and the level of system integration), and improvements in production technology and labor productivity. Consequently, when using a CER equation that incorporates a time variable, the analyst must ensure that the same factors will be operating in the future, and that they will operate in the same manner. Clearly, the opacity of such time variables makes this a nontrivial task.

The specific measure of time we examined in our analysis was the aircraft's date of first flight (in months since January 1, 1940). After examining the relevant full-sample residual plots, we looked at two forms of the first flight date (FFD)—linear and logarithmic. Given the logarithmic form of the *dependent* variable, the linear form of FFD results in an accelerating rate of cost increase (assuming a first flight date coefficient greater than zero), while the logarithmic form of FFD results in a decelerating rate (assuming an exponent of less than one). Unfortunately, we have no a priori notions with respect to whether the rate of increase is increasing or decreasing.

The results of our analysis are summarized in Table 19. As indicated, from a statistical standpoint, the two sets are essentially identical. Furthermore, all of the time-related residual patterns have been eliminated, and with the exception of the tooling equation, both sets have standard errors of estimate that are either roughly equal to or better than those of the 13-aircraft post-1960 equation set (see Table 20).

In short, the introduction of a time variable solves the underestimation problem and generally results in CERs with standard errors of estimate lower than those of the recommended equation set. Unfortunately, there is one major difficulty—we are unable to say which of

Table 19

EQUATION SETS INCORPORATING ALTERNATIVE FORMS OF TIME VARIABLE

Equation	R^2	SEE	F	N
Part A: Linear Incorporation of First Flight Date				
$ENGR_{100} = .00851\ EW^{.712}_{(.000)}\ SP^{.816}_{(.000)}\ e^{.00389 \times FFD}_{(.000)}$	.84	.37	54	34
$TOOL_{100} = .0691\ EW^{.760}_{(.000)}\ SP^{.568}_{(.000)}$	.78	.36	55	34
$LABR_{100} = .172\ EW^{.852}_{(.000)}\ SP^{.402}_{(.001)}$	.87	.29	103	34
$MATL_{100} = .108\ EW^{.894}_{(.000)}\ SP^{.654}_{(.000)}\ e^{.00200 \times FFD}_{(.000)}$	.90	.29	93	34
$DS = .00893\ EW^{.748}_{(.000)}\ SP^{1.10}_{(.001)}\ e^{.00348 \times FFD}_{(.000)}$	.60	.73	15	34
$FT = .00778\ EW^{.585}_{(.000)}\ SP^{1.03}_{(.000)}\ TESTAC^{.939}_{(.000)}\ e^{.00309 \times FFD}_{(.003)}$	.79	.52	27	34
$QC_{100} = .085 \times LABR_{100}$ if cargo	—	—	—	3
$= .127 \times LABR_{100}$ if noncargo	—	—	—	19
$PROG_{100} = 2.82\ EW^{.802}_{(.000)}\ SP^{.649}_{(.000)}\ e^{.00140 \times FFD}_{(.000)}$	.89	.27	79	34
Part B: Logarithmic Incorporation of First Flight Date				
$ENGR_{100} = .000156\ EW^{.685}_{(.000)}\ SP^{.787}_{(.000)}\ FFD^{1.00}_{(.000)}$	.84	.36	54	34
$TOOL_{100} = .0691\ EW^{.760}_{(.000)}\ SP^{.568}_{(.000)}$	.78	.36	55	34
$LABR_{100} = .172\ EW^{.852}_{(.000)}\ SP^{.402}_{(.001)}$	.87	.29	103	34
$MATL_{100} = .00704\ EW^{.874}_{(.000)}\ SP^{.629}_{(.000)}\ FFD^{.698}_{(.000)}$	.91	.28	99	34
$DS = .000265\ EW^{.735}_{(.000)}\ SP^{1.07}_{(.001)}\ FFD^{.873}_{(.010)}$	.60	.73	15	34
$FT = .000271\ EW^{.556}_{(.000)}\ SP^{.966}_{(.001)}\ TESTAC^{.968}_{(.000)}\ FFD^{.877}_{(.001)}$	.80	.50	30	34
$QC_{100} = .085 \times LABR_{100}$ if cargo				3
$= .127 \times LABR_{100}$ if noncargo				19
$PROG_{100} = .647\ EW^{.811}_{(.000)}\ SP^{.636}_{(.000)}\ FFD^{.371}_{(.004)}$	.89	.27	80	34

Table 20

STANDARD ERROR OF ESTIMATE (LOG)

Cost Element	13-Aircraft Post-1960 Sample	34-Aircraft Sample with Linear FFD	34-Aircraft Sample with Logarithmic FFD
Engineering	0.55	0.37	0.36
Tooling	0.25	0.36	0.36
Manufacturing labor	0.31	0.29	0.29
Manufacturing material	0.30	0.29	0.28
Development support	0.82	0.73	0.73
Flight test	0.48	0.52	0.50
Total program cost	0.36	0.27	0.27

the two FFD forms will more accurately reflect future industry experience. The statistical analysis, which included an examination of residuals, indicated that the two sets are virtually equivalent in terms of explaining the variation *within* the database. The inability to distinguish a preferred variable form has significant implications for estimating the costs of future aircraft. As illustrated in Fig. 4, for an aircraft with a projected first flight date of 1995, the difference in assumptions (linear FFD vs. logarithmic FFD) leads to a difference in estimated cost of roughly 50 percent. Because of this large variation, we do not recommend use of either equation set incorporating the time variable. We feel it more judicious to use the equation set without a time variable and to explicitly identify potential changes, estimate their likely effect, and then adjust either the equations or resulting estimates accordingly.

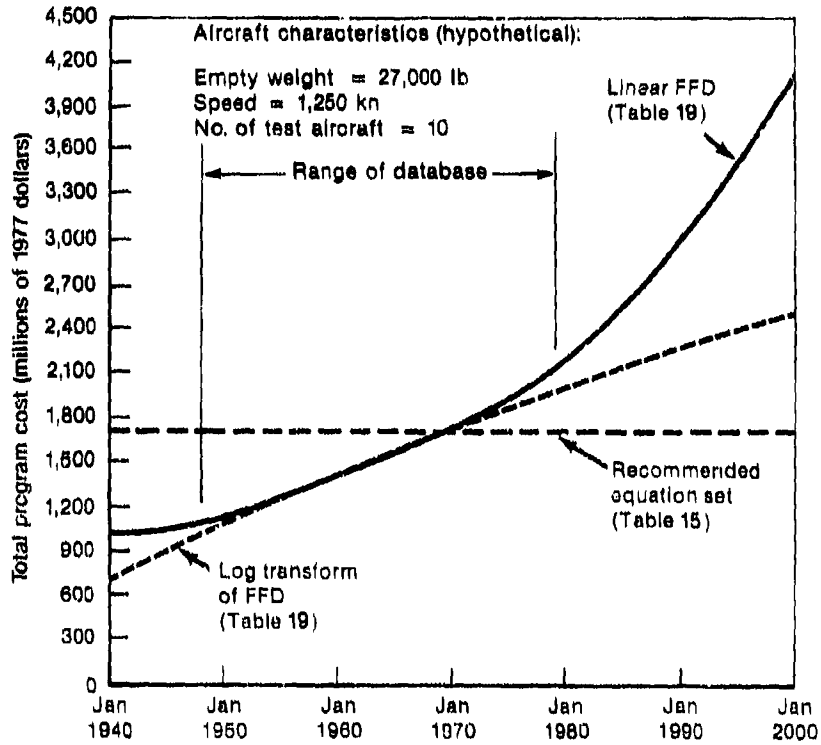

Fig. 4—Total program cost as a function of time
(based on sum of individual elements)

VI. FIGHTER RESULTS

RECOMMENDED SET OF CERs

The recommended set of fighter airframe CERs (Table 21) utilizes only one variable—airframe unit weight—and is based on a subsample of six post-1960 fighters.[1] This equation set provides results that we believe to be more credible than those produced by multiple least-squares regression analysis of the full 17-aircraft fighter sample. Basically, we were not entirely satisfied with the results of the regression

Table 21

SET OF AIRFRAME CERs BASED ON SAMPLE OF 6 POST-1960 FIGHTERS

$$ENGR_{100} = 2.31\ AUW^{.887}$$

$$TOOL_{100} = 1.38\ AUW^{.883}$$

$$LABR_{100} = 25.4\ AUW^{.678}$$

$$MATL_{100} = 43.3\ AUW^{.878}$$

$$DS = .75 \times ENGRC_1$$

$$FT = 27100\ TESTAC^{.687}$$

$$QC = .142 \times LABR_{100}$$

$$PROG_{100} = 550\ AUW^{.812}$$

NOTES: $ENGRC_1$ can be estimated as follows: $ENGRC_1 = .470 \times ENGR_{100} \times \$27.50/hr$, where .470 is the nonrecurring portion of the total engineering effort for the first 100 aircraft, and \$27.50 is the fully burdened hourly engineering rate in 1977 dollars.

Suggested cost-quantity slopes and labor rates to be used in conjunction with this set are provided in Appendix D.

[1]The complete fighter analysis is provided in Note N-2283/2-AF, *Aircraft Airframe Cost Estimating Relationships: Fighters*

analysis of the full fighter sample. We were able to identify only a single acceptable estimating relationship for both the labor and material cost elements (which together account for roughly 50 percent of total cost), and in neither case did the relationship include a performance variable. Furthermore, during the course of the analysis we identified a *tendency* for all the fighters except one to cluster by time period, as shown in Fig. 5. (The F-16 is the exception to the clustering pattern.) Unfortunately, we were not able to adequately address the underlying causes of this clustering. But since these CERs are intended primarily for prediction and not for historical analysis, it seemed quite logical to take advantage of the clustering observation. In short, the post-1960 fighters appeared to be a better guide to the costs of future fighters than did the full fighter sample.

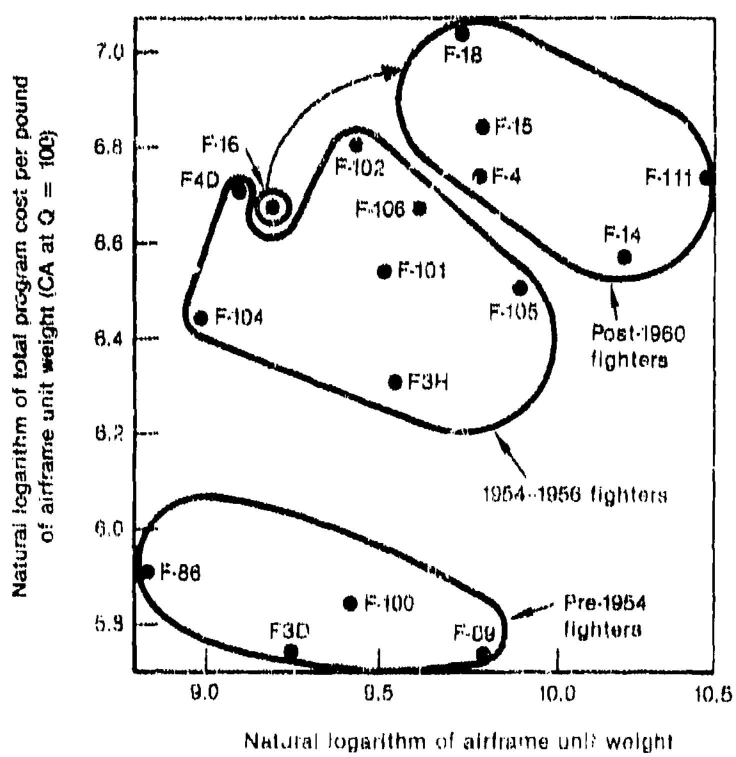

Fig. 5—Typical fighter cluster pattern

Since there were only six observations in the post-1960 sample, one of which was always an outlier and another of which was occasionally an outlier, the equations were determined by subjectively fitting a line to the plot points and then backing into the initial coefficient and variable exponent. The fitting for each cost element was based on a single variable, airframe unit weight (except for flight test, where the number of test aircraft was utilized). The ranges of characteristic values of the six fighters are shown below:

Characteristic	Post-1960 Database Range
Airframe unit weight, lb	9,565 – 33,150
Empty weight, lb	14,062 – 46,170
Speed, kn	1,000+ – 1,250+
Specific power, hp/lb	1.94 – 4+
Climb rate, ft/min	11,600 – 50,000+
Number of flight-test aircraft	7 – 20

Note that while specific power and climb rate still vary over a fairly large range, the range of speed values has become fairly narrow.

CONSTRUCTION/PROGRAM VARIABLES

With the exception of a variable that distinguishes the older fighters (which were essentially gun platforms) from the more modern fighters (which have sophisticated fire control and missile armament), our attempts to incorporate construction and program characteristics were not successful. Although several of the variables characterizing equipment placed within the airframe structure were found to be statistically significant, they did not generally result in any substantial improvement in the quality of the equations. In most cases, the equations incorporating such variables did not produce results that we viewed as credible. Moreover, even in those few instances where the equations did produce credible results, the reduction in the standard error of estimate was never more than two or three percentage points.

TECHNOLOGY INDEX

We were able to identify only one equation (that for the engineering cost) in which the objective technology index (PFFD) was significant at the 5 percent level in the context of the tested variable combination (size/performance/technology index):

$$\text{ENGR}_{100} = .00242\ \text{AUW}^{.13}_{(.000)}\ \text{SPPWR}^{367}_{(.021)}\ \text{PFFD}^{697}_{(.016)}$$

	R^2	SEE	F
ENGR_{100}	.97	.16	134

where

AUW = airframe unit weight (lb)
PFFD = predicted first flight date (months since January 1, 1940)
SPPWR = specific power (hp/lb)

However, the correlation of AUW and SPPWR with the technology index is greater than 0.9. Furthermore, the equation offers little advantage (in terms of the standard error of estimate) over alternative forms that do not have the technology index. We conclude that this index, as now defined, is of little benefit to fighter airframe CERs. This measure is really a composite performance variable and consequently very highly correl[illegible] with most of the performance variables we tested; when treated [illegible] performance variable rather than as a technology index, it is about as good an explanatory variable as speed and specific power.

COMPARISON WITH FULL ESTIMATING SAMPLE EQUATION SET

Table 22 compares how accurately the full estimating sample equation set (Table 15) and the fighter subsample equation set (Table 21) estimate the costs of the six post-1960 fighters. On an *overall average* basis, the fighter equation set does slightly better. However, the two sets differ considerably with respect to which will produce the higher estimate. As shown below, the fighter equation set produces considerably higher estimates than the full sample equation set for the F-16 and F-18:

	Percent by Which Fighter Set Estimate Exceeds All-Mission Set Estimate	
Aircraft	Sum of Elements	Total Program CER
F-16	8	3
F-18	22	22

Table 22

RELATIVE ACCURACY OF ESTIMATES OBTAINED USING FULL ESTIMATING SAMPLE AND FIGHTER SUBSAMPLE EQUATION SETS

(Percent by which actual cost exceeds (+) or falls short of (−) estimated cost)

	Sum of Elements		Total Program CER	
Aircraft	All-Mission Sample	Fighter Sample	All-Mission Sample	Fighter Sample
F-4	−14	−5	−16	−4
F-111	+3	+6	+7	+7
F-14	−22	−17	−20	−16
F-15	−15	−1	−5	+7
F-16	−23	−33	−20	−23
F-18	−33	+18	−36	+22
Average of absolute values	18	13	17	13
Number underestimated (+)	2	2	2	3
Number overestimated (−)	4	4	4	3

However, for the remaining fighters, all of which are heavier and faster than the F-16 and F-18, the all-mission type equation set tends to produce greater estimates:

	Percent by Which All-Mission Set Estimate Exceeds Fighter Set Estimate	
Aircraft	Sum of Elements	Total Program CER
F-4	2	11
F-111	4	1
F-14	4	4
F-15	15	13

Exactly which equation set will provide the higher estimate in any given situation depends on a number of factors, including the aircraft's absolute weights (airframe unit and empty) and speed, and also the relative difference in its empty weight and airframe unit weight. In general, however, it appears that the all-mission-type equation set will produce higher estimates for relatively heavy, fast fighters, while the fighter equation set will produce higher estimates for relatively light, "slow" fighters.

VII. BOMBER/TRANSPORT RESULTS

RECOMMENDED SET OF CERs

We were not able to identify any acceptable estimating relationships for any of the individual cost elements or for total program cost.[1] We believe this failure can be attributed to three factors:

1. Lack of variation in performance variables.
2. The distribution of aircraft with respect to size.
3. The heterogeneity of the sample.

Lack of Variation in Performance Variables. Common sense suggested that the B-58 did not belong in the bomber/transport sample. It is a relatively small, supersonic aircraft, while the remaining bombers and transports are relatively large and subsonic. Furthermore, the data plots, especially the engineering, material, development support, and total program cost plots, showed the B-58 to be *considerably* more expensive on a per pound basis than the other bomber/transport aircraft. Consequently, we excluded the B-58 from our analysis of the bomber/transport sample. As a result, most of the variation in the principal performance measures (speed and climb rate) was lost.

Distribution of Aircraft with Respect to Size. Because they are at the extremes of the bomber/transport sample with respect to size, the B/RB-66 and C-5 are identified as influential observations in nearly every equation documented in Note N-2283/3-AF. This point is easily visualized from Fig. 6. However, we did not feel that size alone was a sufficient reason for excluding the aircraft from the analysis. Furthermore, any attempts to develop simple scaling relationships without the B/RB-66 and C-5 are likely to prove futile, since four of the five remaining aircraft (KC-135, B-52, C-133, and C-141) tend to line up vertically with respect to weight (dashed box in Fig. 6).

Heterogeneity of the Sample. In addition to being small, the sample is not as homogeneous as it appears at first glance:

- The C-130 and C-133 are propeller-driven aircraft.
- The B/RB-66 and KC-135 were evolutionary developments.

[1]See Note N-2283/3-AF, *Aircraft Airframe Cost Estimating Relationships: Bombers and Transports.*

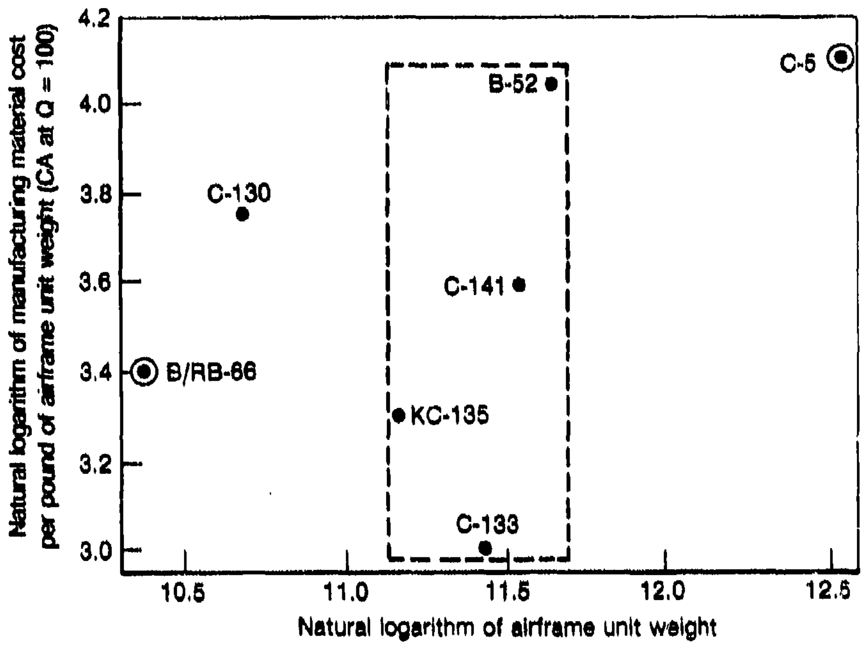

Fig. 6—Typical bomber/transport plot pattern

- The B-52 was into its fourth series (the "D" version) by the time 100 aircraft had been produced.
- A very large proportion (approximately 50 percent) of C-141 costs represent subcontract effort; this may have distorted the distribution of equivalent in-plant cost (Ref. 2, p. 50).
- The C-5 program utilized the acquisition concepts of total package procurement and concurrent development and production.

Given this much diversity in such a small sample, it would have been surprising if we had been able to develop a credible set of CERs.

CONSTRUCTION/PROGRAM VARIABLES

The construction/program variables proved to be of little help in improving the quality of the bomber/transport CERs. Each of the size/program and size/construction equations that met our initial screening criterion with respect to variable significance had difficulties that made it unacceptable.

VIII. ATTACK AIRCRAFT RESULTS

RECOMMENDED SET OF CERs

We were not able to identify any acceptable estimating relationships for any of the individual cost elements.[1] We believe this failure can be attributed to three factors:

1. Lack of variation in performance variables.
2. The distribution of aircraft with respect to size.
3. The heterogeneity of the sample.

Lack of Variation in Performance Variables. The speeds and climb rates for all the sample aircraft except the A-5 are clustered in rather narrow ranges: 400- to 550-kn speed, and 5,000- to 8,000-ft/min climb rate.

Distribution of Aircraft with Respect to Size. Because it is at an extreme of the attack aircraft sample with respect to size, the A-4 is identified as an influential observation in nearly every equation documented in Note N-2283/4-AF. This point is easily seen in Fig. 7. However, we did not feel that small size was sufficient reason for excluding the A-4. Furthermore, any attempts to develop simple scaling relationships without the A-4 would result in equations that show extremely strong diseconomies of scale, with respect to size.

Heterogeneity of the Sample. In addition to being small, the sample is not as homogeneous as it appears at first glance:

- The A-5 is a Mach 2 aircraft, while all the other sample aircraft are subsonic. Similarly, the A-5 climb rate is over twice that of all other attack aircraft.
- The S-3 places considerably more emphasis on electronics than any of the other sample aircraft; this is reflected in its black box count and its ratio of avionics weight to airframe unit weight, both of which fall approximately two standard deviations from the mean.
- The A-10 utilized the acquisition concepts of competitive prototyping and design-to-cost. In addition, it is the only aircraft in the sample that is not carrier-capable and that does not have swept wings.

[1]See Note N-2283/4-AF, *Aircraft Airframe Cost Estimating Relationship: Attack Aircraft.*

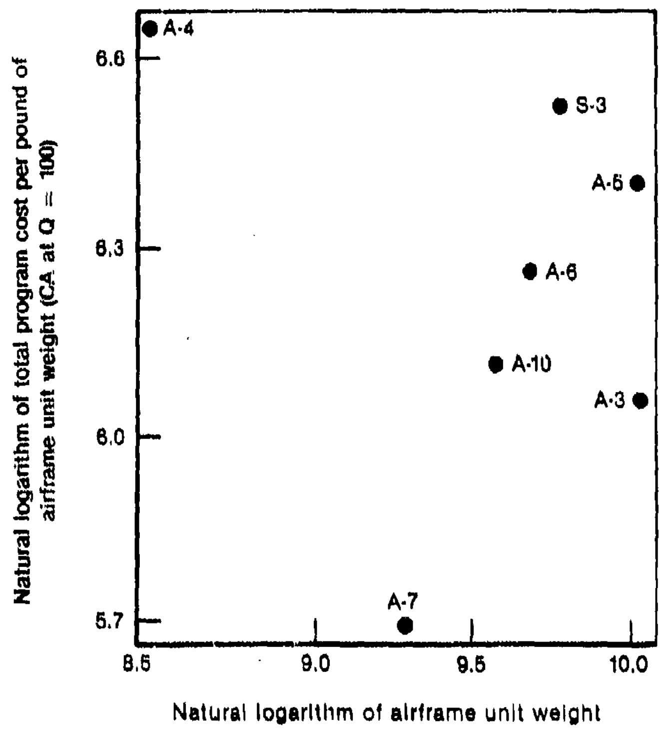

Fig. 7—Typical attack aircraft plot pattern

- The A-7, although classified as a new design, evolved from the F-8.

CONSTRUCTION/PROGRAM VARIABLES

The construction/program variables proved to be of little help in improving the quality of the attack aircraft CERs. Each of the size/program and size/construction equations that met our initial screening criterion with respect to variable significance had difficulties that made it unacceptable.

IX. CONCLUSIONS

DEVELOPMENT OF AN UPDATED SET OF AIRFRAME CERs

The equation set that we feel is most generally applicable to and will most accurately reflect the range of estimating situations likely to be encountered in the future is the one presented in Table 15 (p. 46). It is based on a subsample of 13 post-1960 aircraft. We believe that the post-1960 experience is a better guide to the future than the full-sample experience, which dates back to 1948.

Empty weights for the sample aircraft range from under 10,000 lb to over 300,000 lb, while speeds range from 400 kn to over 1,250 kn. The accuracy of the CERs in the recommended equation set (as measured by the standard error of estimate) varies significantly. Four CERs have standard errors of estimate of about 0.30, while three others have standard errors of estimate of about 0.50 or greater. None of the equations meets our goal of 0.18. On the other hand, the lowest standard errors of estimate in the set are associated with cost elements (tooling, labor, and material) that typically account for 66 percent of total program cost at a quantity of 100.

The ultimate test of the set's usefulness will be its capability to estimate the cost of future aircraft. Unfortunately (from an estimating point of view), airframes are changing dramatically with respect to materials (e.g., more extensive use of composites), design concepts (e.g., concepts to increase fuel efficiency and to reduce radar cross section), resources devoted to system integration (e.g., integration of increasingly sophisticated electronics and armament into the airframe), and manufacturing techniques (e.g., utilization of computers and robots). Although we do not have the data to demonstrate it, we feel that the net effect of these changes will be to increase unit costs. In other words, we see no danger that the recommended equation set will overestimate the costs of future aircraft.

OTHER STUDY OBJECTIVES

In addition to attempting to develop an updated set of airframe CERs, this study examined in some detail the following possibilities for improving CER accuracy:

- Stratifying the full estimating sample into subsamples representing major differences in aircraft type.
- Incorporating variables describing program structure and airframe construction characteristics.
- For the fighter aircraft only, incorporating an objective technology index into the equations.

With respect to sample stratification, we examined subsamples based on mission designation—fighter, bomber/transport, and attack. We conclude that this approach offers no particular advantage: We were not able to identify any acceptable estimating relationships for either the bomber/transport or the attack aircraft subsamples. We believe this is attributable to the small number of aircraft in these subsamples plus the fact that the subsamples are not nearly as homogeneous as the mission designations might suggest. For the fighter subsample, weight-scaling relationships were developed for each cost element based on six post-1960 fighters (the F-4, F-111, F-14, F-15, F-16, and F-18).[1] In general, this set of equations will produce larger estimates than the all-mission type equation set for relatively light, "slow" fighters (e.g., the F-16 and F-18) and smaller estimates for relatively heavy, fast fighters (e.g., the F-14, F-111, F-14, and F-15). However, using the average absolute relative deviations of the six post-1960 fighters as a basis, we found that the fighter equation set was only slightly more accurate than the all-mission type set despite the focused database.

We also conclude that the incorporation of variables describing program characteristics and airframe construction characteristics does not improve the overall quality of the equation sets. Although variables characterizing the level of system integration were frequently found to be statistically significant, they did not, as a rule, result in any substantial improvement in the quality of the equations. In most cases, the equations incorporating such variables did not produce results that we viewed as credible. Moreover, even in those few instances where the equations did produce credible results, the reduction in the standard error of estimate was never more than two or three percentage points.

Finally, attempts to incorporate an objective technology index into the fighter estimating relationships were unsuccessful.

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[1]See Table 21 in Sec. VI.

USE OF RESULTS

The following potentially useful information is presented in this report and its supporting Notes:

- Recommended equation sets.
- Plots of cost versus airframe unit weight for each cost element.
- All alternative equations meeting our initial screening criterion with respect to variable significance.

We have presented extensive documentation to assist the analyst in deciding on an appropriate course of action. Although we have selected recommended equation sets, the ultimate responsibility for their application rests with the user, who should review all of the results before selecting equations for a particular situation.

Equation Sets

Recommended sets of CERs have been provided for military aircraft airframes in general and fighter airframes specifically. These equation sets may be used as is, or they may be tailored to fit specific circumstances (i.e., adjustment of initial coefficient). However, even when the sets are used as is, analysts should ensure that the characteristics of the proposed aircraft fall within the range of the database and that the aircraft does not possess any other features (i.e., nondatabase characteristics) that may set it apart.

It is suggested that fighters that fall within the limited range of applicability of the fighter equation set be run through both the subsample set and the full set. Although we were unable to develop any compelling justification for its use, we did determine that the fighter equation set *generally* produces higher estimates for lighter, "slower" fighters than does the full estimating sample set, and lower estimates for heavier, faster fighters. Consequently, we believe that the fighter set should be viewed as a complement to the full estimating sample set. Once the applications have been made, the results of the two models can be contrasted, and only if there is a significant difference in the results will the analyst need to address the question of which estimate to use. Even then, that decision will probably be based largely on personal preference. For example, if there is more concern with the potential adverse effects of underestimation than with those of overestimation, more weight will clearly be given to the higher of the two estimates.

Data Plots

The data plots in Appendix A and the supporting Notes can be used to estimate the costs of proposed aircraft by analogy.

Alternative Equations

Each supporting Note contains summary tables, by cost element, of all estimating relationships meeting our initial screening criterion (i.e., each variable is significant at the 5 percent level). It is entirely possible that in some situations one of the alternative equations may be more appropriate than the recommended one.

FUTURE WORK

> No study of the type described here is ever complete. One analysis leads to another ad infinitum, until at some point it is necessary to call a halt, present the results, and go on to something else. We have gone down a number of paths suggested by persons inside and outside of RAND and found that most terminate in a cul-de-sac. None of the many independent variables considered offers much hope of improving the reliability of estimates obtained using only weight and speed.[2]

Interestingly, this was the conclusion reached by the analysts who developed the previous set of RAND airframe CERs, and it is equally applicable now.

With respect to future airframe CER efforts, there may be some as-yet-untested variables that will help to improve equation accuracy. Variables that reflect differences in airframe design concepts, materials composition, manufacturing methods, contractor capability, and the system integration effort appear to show the most promise. However, developing unambiguous measures for these characteristics and collecting the necessary data will be a major effort. And if such definition and collection efforts are not expected to be successful,[3] there is probably little merit in undertaking future studies of this type. We say this for two reasons: First, over 60 percent of the aircraft designs in the RAND estimating sample are now more than 25 years old, and only about 10 percent are less than 15 years old. Second, new airframe

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[2]Ref. 3, p. 53.

[3]We admit to skepticism on two counts. First, we doubt that funds would ever be made available to attempt such an undertaking. Second, we think it is problematic whether enough data could be collected for variables such as those described to do a credible statistical analysis at any price

starts have slowed down dramatically (only two *new* airframe designs have entered operational service since 1974—the F-16 and the F-18).[4] Thus, if analysts cannot account for technological and system-integration differences between the older and newer aircraft in the sample, the *relevant* (i.e., technologically similar) estimating sample is probably going to be too small to permit any type of statistical analysis.

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[4]Furthermore, we were able to readily identify only two new airframe designs on the *immediate* horizon—the C-17 and the ATB (Advanced Technology Bomber)—unless we include the possibility of the F-19 (see Ref. 32, p. 7; Ref. 33, p. 11; and Ref. 34, p. 39) in which case there are three. In the *longer* run, only the ATA (Advanced Tactical Attack aircraft) and the ATF (Advanced Tactical Fighter) are readily apparent. Interestingly, a brief review of ongoing and recently concluded Air Force and Navy aircraft procurement indicates that a fair number of aircraft programs have used existing or modified airframes: the AV-8A, AV-8B, B-1B, C-5B, E-3, E-4, EF-111, KC-10, and TR-1.

Appendix A

COST ELEMENT DEFINITIONS AND DATA PLOTS

Work breakdown structure (WBS) categories included in the RAND airframe cost structure are shown in Table A.1.[1] A matrix mapping contractor cost-data reporting (CCDR) categories[2] and relevant WBS categories into specific RAND airframe cost elements is provided in Table A.2.

DEFINITIONS

Engineering

In general, the engineering cost element encompasses the hours expended in the study, analysis, design, development, evaluation, and redesign of the basic airframe as well as the system engineering and project management efforts undertaken by the prime contractor. More specifically, it includes engineering for design studies and integration; for wind-tunnel models, drop model, mockups, and propulsion-system tests; for laboratory testing of components, subsystems, and static and fatigue articles; for preparation and maintenance of drawings and process and materials specifications; and for reliability. Also included are the hours expended for the sustaining engineering function (through the stated quantity). The sustaining function covers such things as customer support/liaison, identifying ways to correct operationally revealed deficiencies, and suggesting possible system improvements. Engineering hours not directly attributable to the airframe itself (those charged to ground-handling equipment, spares, and training equipment) are not included. Engineering hours expended as part of the tool and production-planning function are included with the cost element tooling; those expended as part of the flight-test planning and evaluation effort are included in the flight-test cost element. Material, purchased parts, and test equipment required to accomplish the engineering function are assumed to be included in the fully burdened engineering labor rate.

[1]See MIL-STD-881, *Work Breakdown Structure for Defense Materiel Items.*

[2]See AFLCP 800-15, *Contractor Cost Data Reporting System.*

Table A.1

WBS CATEGORIES INCLUDED IN RAND AIRFRAME COST ELEMENTS

WBS Category	Included?
Air vehicle	
Airframe[a]	Yes
Propulsion[b]	No
Avionics[b]	No
Armament/weapon delivery[b]	No
Training	No
Peculiar support equipment	No
Systems test and evaluation	
Development test	Yes
Technical evaluation	Yes
Operational evaluation	Yes
Mockups	Yes
Test facilities	Yes
Other ST&E	Yes
System/project management	Yes
Data	
Engineering/management data	Yes
ILS data (tech orders and manuals)	No
Operational/site activation	No
Common support equipment	No
Industrial facilities	No
Initial spares and repair parts	No

[a]The term *airframe* refers to the assembled structural and aerodynamic components of the air vehicle that support subsystems essential to a particular mission. It includes, for example, the basic structure (wing, empennage, fuselage, and associated manual flight control system), the air induction system, starters, exhausts, the fuel control system, inlet control system, alighting gear (tires, tubes, wheels, brakes, hydraulics, etc.), secondary power, furnishings (cargo, passenger, troop, etc.), engine controls, instruments (flight navigation, engine, etc.), environmental control, racks, mounts, and intersystem cables and distribution boxes, etc., which are inherent to and inseparable from the assembled structure, dynamic systems, and other equipment homogeneous to the airframe. All efforts directly related to propulsion, avionics, and armament are excluded.

[b]Installation of the propulsion, avionics, and armament subsystems is acounted for in the airframe category; the design integration effort is included in system/project management; and some testing is included in system test and evaluation.

Table A.2

RAND AIRFRAME COST ELEMENTS

WBS Category	CCDR Categories[a]									
	Engineering		Tooling		Manufacturing Labor		Manufacturing Material		Quality Control	
	NR	R	NR	R	NR	R	NR	R	NR	R
Air vehicle										
Airframe	Engr	Engr	Tool	Tool	DS	Labr	DS	Matl	QC	QC
Systems test & evaluation										
Development tests	Engr	—	DS	—	DS	—	DS	—	DS	—
Technical evaluation	FT	—	FT	—	FT	—	FT	—	FT	—
Operational evaluation	FT	—	FT	—	FT	—	FT	—	FT	—
Mockups	Engr	—	DS	—	DS	—	DS	—	DS	—
Test facilities	Engr	—	DS	—	DS	—	DS	—	DS	—
Other ST&E	Engr	—	DS	—	DS	—	DS	—	DS	—
System/project management	Engr	Engr	DS	Tool	DS	Labr	DS	Matl	DS	QC
Engineering/management data	Engr	Engr	—	—	—	—	—	—	—	—

[a]NR = nonrecurring; R = recurring; Engr = engineering; Tool = tooling; Labr = manufacturing labor; Matl = manufacturing material; DS = development support; FT = flight test; QC = quality control.

Tooling

Tooling refers only to those tools designed for use on a specific program, i.e., assembly tools, dies, jigs, fixtures, master forms, gauges, handling equipment, load bars, work platforms, and test and checkout equipment. General-purpose tools such as milling machines, presses, routers, and lathes (except for the cutting instruments) are considered capital equipment. If such equipment is owned by the contractor (much of it is government-owned), an allowance for depreciation is included in the overhead account. Tooling hours include all effort expended in tool and production planning, design, fabrication, assembly, installation, modification, maintenance, and rework, and programming and preparation of tapes for numerically controlled machines. The cost of the material used in the manufacture of the dies, jigs, fixtures, etc., is assumed to be included in the fully burdened tooling labor rate.

Manufacturing Labor

Manufacturing labor is all the direct labor necessary to machine, process, fabricate, and assemble the major structure of an aircraft and to install purchased parts and equipment, engines, avionics, and ordnance items, whether contractor-furnished or government-furnished. Manufacturing man-hours include the labor component of off-site manufactured assemblies and effort on those parts which, because of their configuration or weight characteristics, are design-controlled for the basic aircraft. These parts normally represent significant proportions of airframe weight and of the manufacturing effort and are included regardless of their method of acquisition. Such parts specifically include actuating hydraulic cylinders, radomes, canopies, ducts, passenger and crewseats, and fixed external tanks. Man-hours required to fabricate purchased parts and materials are excluded from the cost element. Nonrecurring labor undertaken in support of engineering during the development phase is included in the development support cost element.

Manufacturing Material

Manufacturing material includes raw and semifabricated materials plus purchased parts (standard hardware items such as electrical fittings, valves, and hydraulic fixtures) used in the manufacture of the airframe. This category also includes purchased equipment, i.e., items such as motors, generators, batteries, landing gear, air conditioning equipment, instruments, and hydraulic and pneumatic pumps, whether procured by the contractor or furnished by the government. Where such equipment is designed specifically for a particular aircraft, it is considered as subcontracted, not as purchased equipment, and is therefore included in the manufacturing labor cost element. Nonrecurring material used in support of engineering during the development phase is included in the development-support cost element.

Development Support

Development support is the nonrecurring manufacturing effort undertaken in support of engineering during the development phase of an aircraft program. It is intended to include the man-hours and material required to produce mockups, models, test parts, static test items, and other hardware items (excluding complete flight-test aircraft) needed for airframe development.

Flight Test

Flight test includes all costs incurred by the contractor in the conduct of flight testing except production of the test aircraft. Engineering planning, data reduction, manufacturing support, instrumentation, all other materials, fuel and oil, pilot's pay, facilities, rental, and insurance costs are included. Flight-test costs incurred by the Air Force, Army, or Navy are excluded.

Quality Control

Quality control refers to the hours expended to ensure that prescribed standards are met. It includes such tasks as receiving inspection; in-process and final inspection of tools, parts, subassemblies, and complete assemblies; and reliability testing and failure-report reviewing. The preparation of reports relating to these tasks is considered direct quality-control effort.

Total Program Cost

Total program cost is the sum of the seven preceding cost elements. Engineering, tooling, manufacturing labor, and quality-control hours for each aircraft program were converted to 1977 dollars using the following industry-average composite hourly rates:

Element	Hourly Rate ($)
Engineering	27.50
Tooling	25.50
Manufacturing labor	23.50
Quality control	24.00

These composite rates include direct labor, overhead, general and administrative expense, and miscellaneous direct charges (travel, per diem, etc.), and in the case of engineering and tooling, material costs as well. Fee is not included.

DATA PLOTS

Plots of cost per pound as a function of airframe unit weight are provided in Figs. A.1 through A.8 for engineering, tooling, manufacturing labor, manufacturing material, development support, flight test, quality control, and total program cost, respectively. The F-16 and F-18 are not shown because of proprietary restrictions.

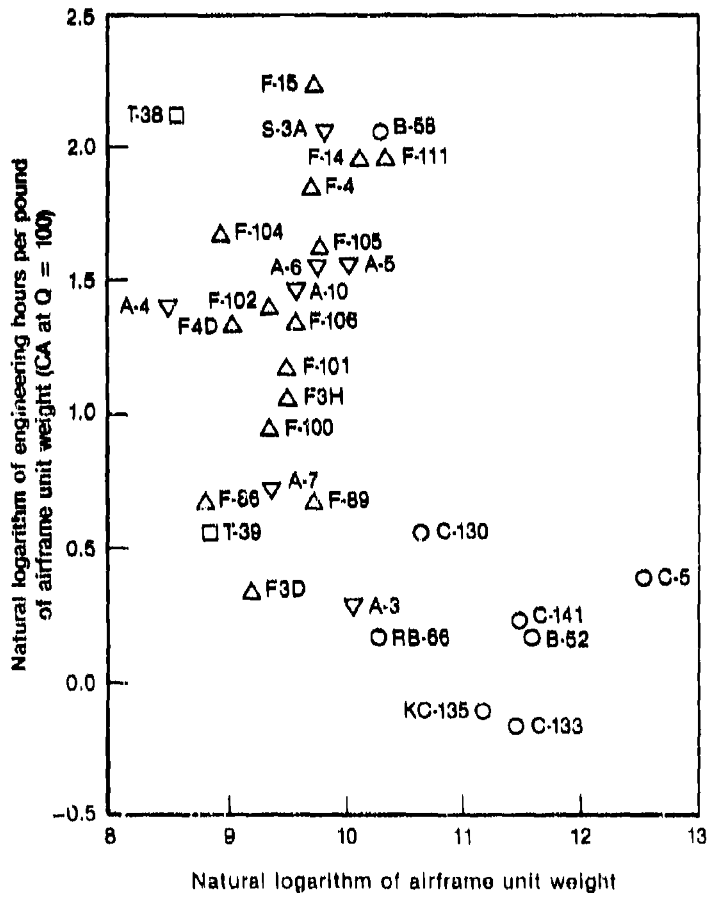

Fig. A.1—Engineering hours per pound as a function of airframe unit weight

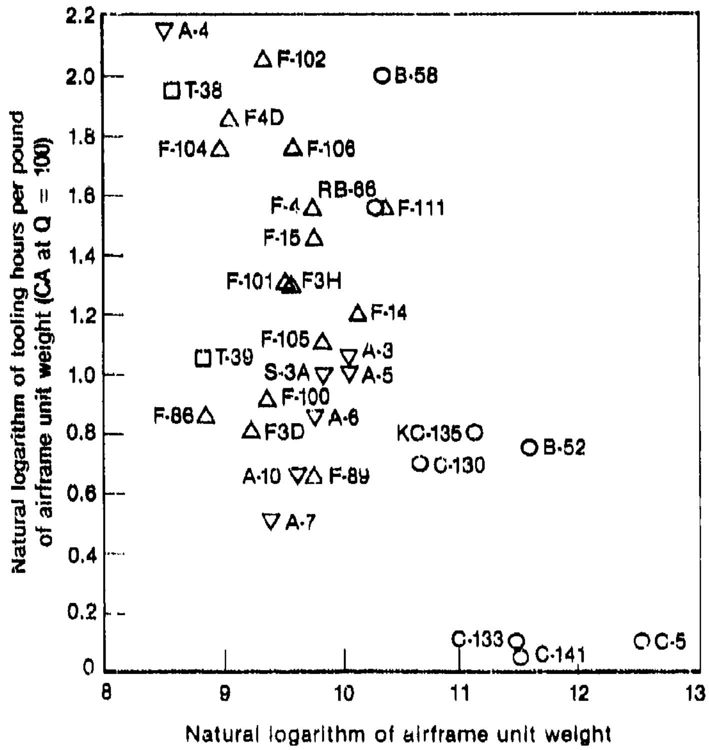

Fig. A.2—Tooling hours per pound as a function of airframe unit weight

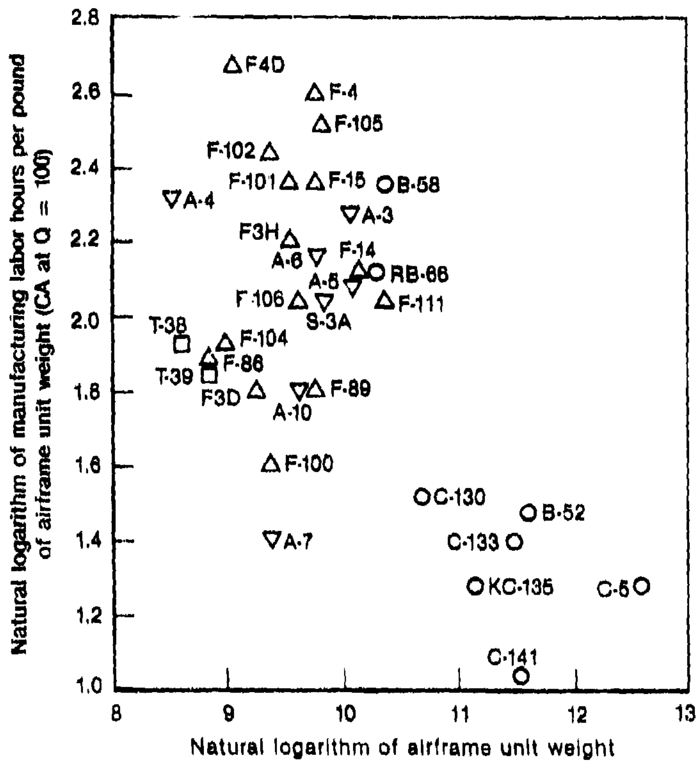

Fig. A.3—Manufacturing labor hours per pound as a function of airframe unit weight

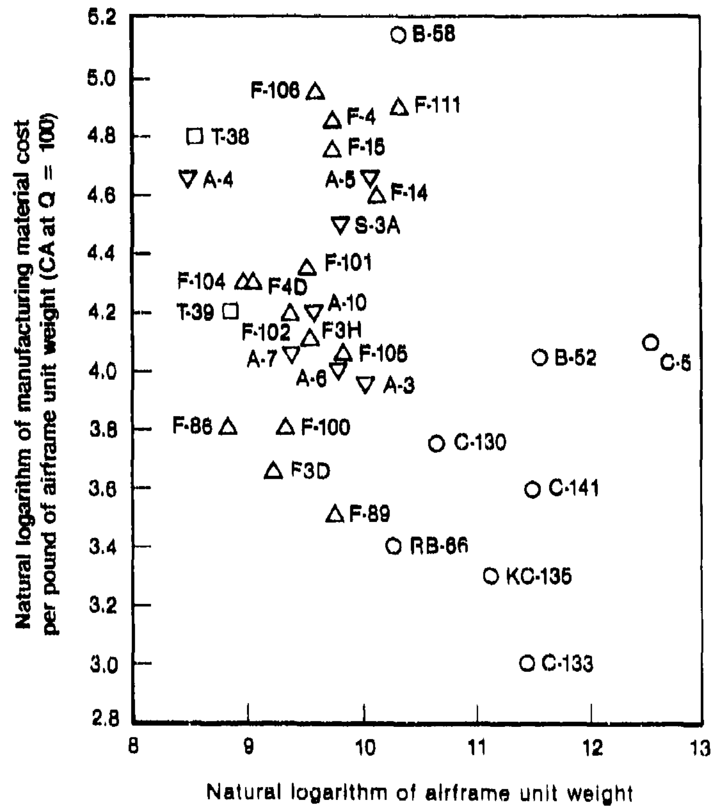

Fig. A.4—Manufacturing material cost per pound as a function of airframe unit weight

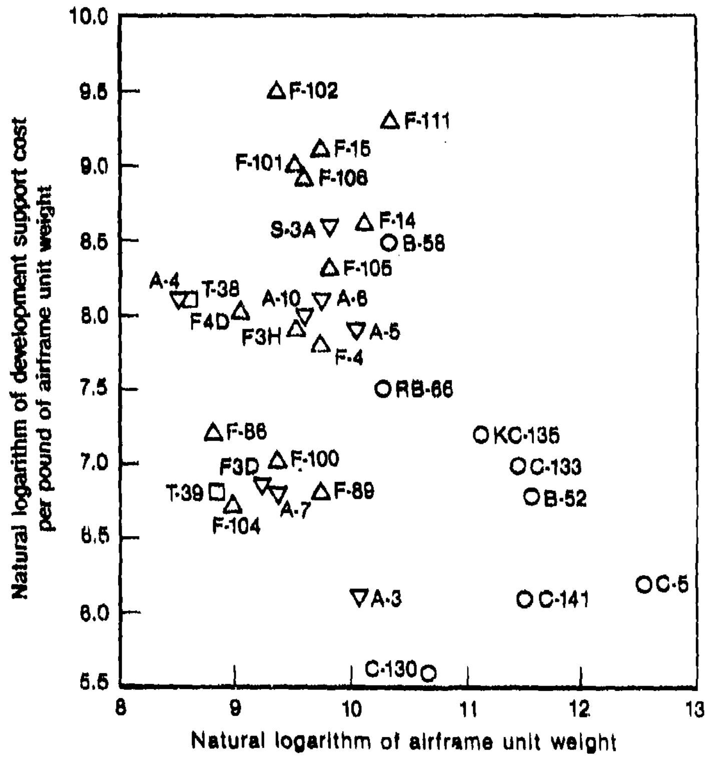

Fig. A.5—Development support cost per pound as a function of airframe unit weight

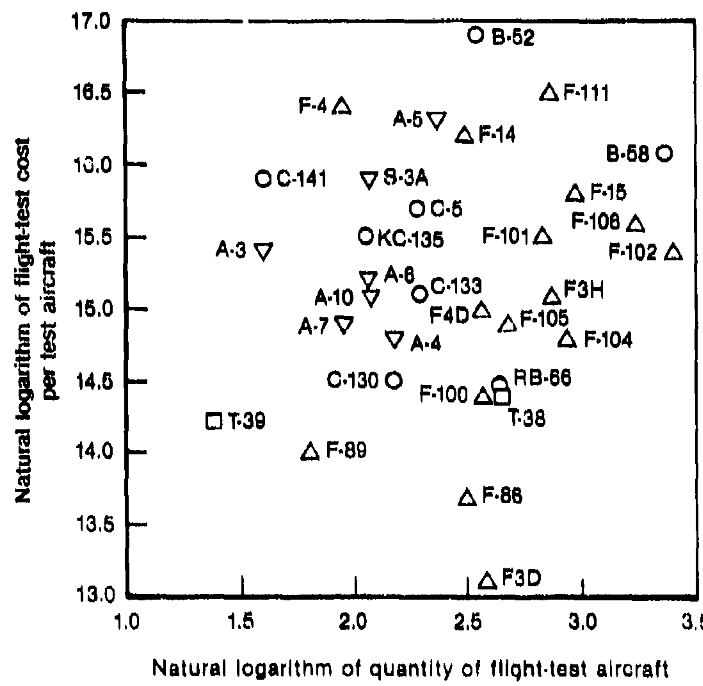

Fig. A.6—Flight-test cost per test aircraft as a function of the quantity of flight-test aircraft

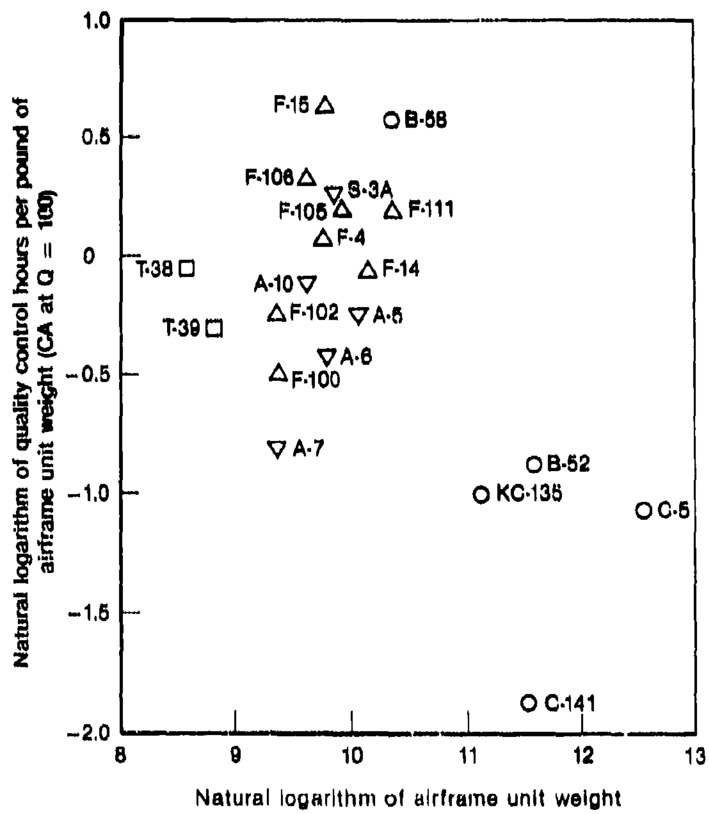

Fig. A.7—Quality control hours per pound as a function of airframe unit weight

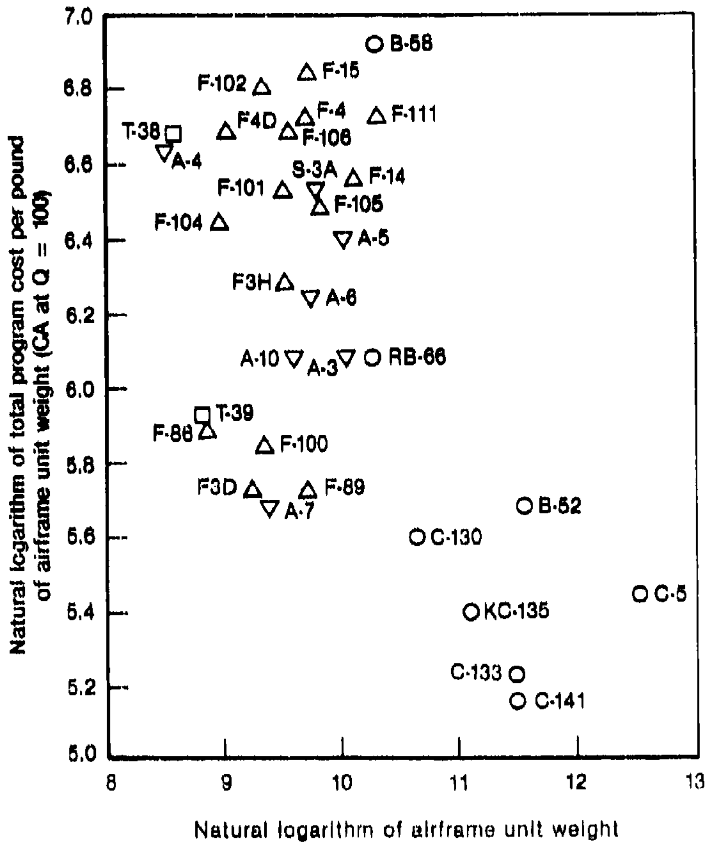

Fig. A.8—Total program cost per pound as a function of airframe unit weight

Appendix B

EXPLANATORY VARIABLE DEF'NITIONS AND VALUES

SIZE

Airframe Unit Weight: Empty weight (in pounds at Q = 100) minus wheels, brakes, tires, and tubes; main and auxiliary engines; rubber or nylon fuel cells; main and auxiliary starters; propellers; auxiliary powerplant unit; instruments; batteries and electrical power supply and conversion; avionics group; turrets and power-operated mounts; air conditioning, anti-icing and pressurization units and fluids; cameras and optical viewfinders; trapped fuel and oil.

Empty Weight: The weight of the aircraft (in pounds) with no fuel, ordnance, or crew aboard.

Wetted Area: Total surface area of aircraft (in square feet).

TECHNICAL/PERFORMANCE

Maximum Speed: Maximum speed, in knots, at any altitude.

Speed Class: Categorical variable signifying whether maximum speed is less than M 0.95 (=1), greater than or equal to M 0.95 but less than M 1.94 (=2); greater than or equal to M 1.95 but less than M 2.5 (=3); or greater than or equal to M 2.5 (=4).

Specific Power (fighters only): The product of the maximum installed sea-level static thrust and the maximum velocity divided by the combat weight, expressed in units of horsepower per pound. The conversion factor to go from pound-knots per pound to horsepower per pound is 0.00307 (1 kn = 101.34 ft/min, and 1 hp = 33,000 ft-lb/min).

Maximum Specific Energy (fighters only): The maximum value (in feet) of the sum of kinetic and potential energy the aircraft develops in 1-g level flight divided by the combat weight.

Climb Rate: The maximum rate of climb at sea level in feet/minute.

Maximum Sustained Load Factor (fighters only): The maximum load factor (in g's) the aircraft can sustain in level flight at an altitude of 25,000 ft, at Mach 0.8 at its combat weight.

Breguet Range Factor (fighters only): The maximum value (in nautical miles) of the product of the average cruise speed and lift-to-drag ratio divided by the specific fuel consumption (the coefficient of the logarithmic term of the Breguet range equation).

Useful Load Fraction: The difference between maximum gross weight and empty weight, divided by maximum gross weight.

Predicted First Flight Date (fighters only): First flight date measured in months since January 1, 1940, as estimated by the technology index equation for new designs described in Sec. I.

CONSTRUCTION

Design Ultimate Load Factor: The maximum load factor (in g's) the aircraft is designed to withstand at the stress design weight without structural failure.

Structural Efficiency Factor (fighters only): The structure weight divided by the product of the stress design weight and the design ultimate load factor.

Carrier Capability Designator: A categorical variable signifying whether the aircraft is carrier capable (=2) or not (=1).

Engine Location Designator: A categorical variable signifying whether engines are embedded in the fuselage (=1) or located in nacelles under the wing (=2).

Wing Type Designator: A categorical variable signifying straight wing (=1), swept wing (=2), delta wing (=3), or variable-sweep wing (=4).

Ratio of Wing Area to Wetted Area: The ratio of the reference area of the wing to the total surface area of the aircraft.

Ratio of Quantity (Empty Weight Minus Airframe Unit Weight) to Airframe Unit Weight: The empty weight and airframe unit weight as previously defined.

Ratio of Avionics Weight to Airframe Unit Weight: The ratio of total avionics-suite weight (installed) to airframe unit weight.

Number of Black Boxes: The number of identifiable electronics items in communication, navigation, identification, fire control, ECM, and data processing functions. See Sec. II for additional explanation.

PROGRAM

Number of Test Aircraft: The number of test aircraft used in the flight-test program.

Maximum Tooling Capability: The maximum monthly tooling rate for the program. The maximum tooling rate is defined as the rate achievable with the tools that were on hand, operating with (1) a first shift, (2) a second, "swing" shift, consisting of a full complement of production workers and necessary supervisory staff, and (3) a third shift, "as required" for certain production operations and for repair and maintenance of the tooling.

New Engine Designator: A categorical variable signifying whether airframe incorporated a new engine (=2) or not (=1). See Sec. II for additional explanation.

Contractor Experience Designator: A categorical variable signifying whether the company that developed and produced the subject aircraft had recent experience in developing and producing the same mission-type aircraft (=1) or not (=2). See Sec. II for additional explanation.

Weapon System Designator (fighters only): A categorical variable signifying whether the aircraft was developed with emphasis on missiles and sophisticated fire control systems (=2) or gun armament (=1). See Sec. II for additional explanation.

Program-Type Designator: A categorical variable signifying the type of development program, prototype (=2) or concurrent (=1). A prototype program is one in which the first lot consists of three aircraft or less. See Sec. II for additional explanation.

Explanatory-variable values are presented in Tables B.1, B.2, and B.3. Primary data sources were official Air Force aircraft and propulsion characteristic summaries and Refs. 17 and 24 through 30.

Table B.1

EXPLANATORY VARIABLE VALUES: SIZE AND TECHNICAL/PERFORMANCE

	Size				Technical/Performance								
Aircraft	Airframe Unit Weight (lb)	Empty Weight (lb)	Wetted Area (ft^2)	Maximum Speed (kn)	Speed Class	Specific Power	Maximum Specific Energy	Climb Rate (ft/min)	Maximum Sustained Load Factor	Thrust to Weight Ratio	Breguet Range Factor	Useful Load Fraction	Predicted First Flight Date
A-3	23,031	35,900	3,800	548	1	X	X	5,050	X	X	X	.486	X
A-4	5,072	9,146	1,144	586	1	X	X	8,400	X	X	X	.504	X
A-5	23,400	32,714	2,050	1147	3	X	X	27,900	X	X	X	.439	X
A-6	17,150	26,208	2,100	561	1	X	X	10,000	X	X	X	.583	X
A-7	11,621	15,497	1,600	595	1	X	X	8,580	X	X	X	.578	X
A-1	14,842	19,858	2,463	380	1	X	X	6,100	X	X	X	.550	X
B-5	112,072	177,816	10,050	551	1	X	X	5,120	X	X	X	.605	X
B-5	32,680	55,560	5,450	1147	3	X	X	17,830	X	X	X	.650	X
B/RB-66	30,490	42,549	4,372	548	1	X	X	5,000	X	X	X	.487	X
C-5	270,145	320,085	30,800	496	1	X	X	5,170	X	X	X	.555	X
C-130	43,446	58,107	7,500	320	1		X	X3,900	X	X	X	.532	X
C-133	96,312	114,600	13,150	304	1	X	X	3,400	X	X	X	.617	X
KC-135	70,253	97,030	10,770	527	1	X	X	5,900	X	X	X	.677	X
C-141	104,322	130,900	14,100	491	1	X	X	7,270	X	X	X	.570	X
F3D	10,130	14,800	1,843	470	1	.40	47,700	4,100	.90	.275	3,750	.484	109
F3H	13,808	21,270	1,908	622	1	.80	58,700	15,000	3.00	.466	4,180	.455	174
F4D	8,737	16,050	1,500	628	1	1.41	94,500	20,200	3.50	.731	3,820	.427	107
F-4	17,220	27,530	2,150	1222	3	2.02	140,000	10,000	2.00	.700	4,200	.508	244
F-14	26,500	39,825	3,155	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	355
F-15	17,550	26,795	2,040	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	.499	432
F-16	9,506	14,062	1,300	(a)	2	(a)	(a)	(a)	(a)	(a)	(a)	.574	402
F-18	16,300	20,583	(b)	(a)	2	(b)	(b)	(b)	(b)	(b)	(b)	.439	(b)
F-86	6,788	10,040	1,070	590	1	.07	50,500	7,650	2.00	.307	4,870	.416	142
F-89	18,119	23,870	(b)	546	1	.07	(b)	11,800	2.40	.400	3,070	.347	108
F-100	12,118	18,260	1,500	752	2	1.40	94,400	25,700	3.20	.607	4,920	.371	164
F-101	13,423	24,720	2,060	872	2	1.80	77,700	29,800	2.50	.671	4,530	.493	180
F-102	12,304	19,400	2,150	680	2	1.19	65,700	18,700	3.00	.571	5,300	.374	171
F-104	7,963	11,570	1,078	1150	3	2.48	117,000	51,500	2.70	.703	1,500	.608	217
F-105	19,301	24,500	1,908	1117	3	2.00	93,000	38,300	2.40	.585	5,200	.538	216
F-106	14,020	23,180	2,230	1153	3	2.18	99,000	34,500	3.20	.616	5,400	.363	200
F-111	33,150	43,170	2,580	1262	3	1.94	126,000	12,600	2.00	.601	6,450	.533	267
S-3	18,530	20,581	2,027	429	1	X	X	5,000	X	X	X	.494	X
T-38	5,330	7,110	(b)	699	2	X	X	28,500	X	X	X	.467	X
T-39	[illegible]	9,753	(b)	468	1	X	X	4,270	X	X	X	[illegible]	X

NOTE: X = Values collected for fighter only.
[a]Classified.
[b]Not available.

Table B.2

EXPLANATORY VARIABLE VALUES: CONSTRUCTION

Aircraft	Design Ultimate Load Factor	Structural Efficiency Factor	Carrier Capability Designator	Engine Location Designator	Wing Type[a]	Ratio of Wing Area to Wetted Area	Ratio of (EW-AUW) to AUW	Ratio of Avionics Weight to AUW	No. of Black Boxes
A-3	6.00	X	2	2	2	.200	.50	.085	8
A-4	10.50	X	2	1	2	.227	.80	.084	6
A-5	11.00	X	2	1	2	.237	.39	.110	13
A-6	9.75	X	2	1	2	.251	.48	.170	23
A-7	10.50	X	2	1	2	.222	.33	.059	19
A-10	4.93	X	1	2	1	.205	.34	.041	14
B-52	3.00	X	1	2	2	.240	.58	.070	24
B-58	3.00	X	1	2	3	.283	.70	(c)	26
B/RB 66	4.80	X	1	2	2	.178	.40	.092	(c)
C-5	3.75	X	1	2	2	.201	.15	.017	27
C-130	3.75	X	1	2	1	.230	.34	.085	17
C-133	3.75	X	1	2	1	.203	.19	.021	16
KC-135	3.75	X	1	2	2	.225	.38	(c)	16
C-141	3.75	X	1	2	2	.228	.31	.023	26
F3D	9.00	.0459	2	1	1	.218	.47	.145	9
F3H	11.25	.0372	2	1	2	.272	.53	.060	6
F4D	9.50	.0433	2	1	3	.371	.84	.215	9
F-4	12.75	.0291	2	1	2	.247	.60	.101	14
F-14	(b)	(b)	2	1	4	.179	.39	.112	21
F-15	11.00	.0321	1	1	2	.230	.53	.090	24
F-16	(c)	.0221	1	1	2	.216	.47	(c)	(c)
F-18	(c)	(c)	2	1	2	(c)	.26	(c)	(c)
F-86	11.00	.0328	1	1	2	.269	.48	.106	4
F-89	8.50	.0469	1	1	1	(c)	.32	(c)	9
F-100	11.00	.0368	1	1	2	.255	.51	.016	5
F-101	11.00	.0240	1	1	2	.179	.84	.075	9
F-102	10.50	.0333	1	1	3	.305	.58	.164	9
F-104	11.00	.0335	1	1	2	.182	.45	.076	6
F-105	13.00	.0383	1	1	2	.193	.27	.074	11
F-106	10.50	.0328	1	1	3	.312	.59	.190	11
F-111	11.00	.0340	1	1	4	.203	.39	.081	18
S-3	5.25	X	2	2	2	.229	.44	.220	33
T-38	11.00	X	1	1	2	(c)	.38	(c)	7
T-39	11.00	X	1	2	2	(c)	.39	(c)	10

NOTE: X = values collected for fighters only.
[a]1 = straight; 2 = swept; 3 = delta; 4 = variable sweep.
[b]Classified.
[c]Not available.

Table B.3

EXPLANATORY VARIABLE VALUES: PROGRAM

Aircraft	No. of Test Aircraft	Maximum Tooling Capability	New Engine Designator	Contractor Experience Designator	Weapon System Designator	Program Type Designator
A-3	5	8	1	2	X	2
A-4	9	40	1	1	X	2
A-5	11	6	1	2	X	1
A-6	8	8	2	2	X	1
A-7	7	24	1	1	X	1
A-10	8	15	1	2	X	2
B-52	13	10	2	1	X	2
B-58	30	8	2	2	X	1
B/RB-66	14	10	2	1	X	1
C-5	10	2	2	1	X	1
C-130	9	18	2	2	X	2
C-133	10	2	2	1	X	1
KC-135	8	15	1	1	X	2
C-141	5	9	1	1	X	1
F3D	13	20	1	2	1	2
F3H	18	13	2	1	1	2
F4D	13	20	2	1	1	2
F-4	7	15	1	1	2	1
F-14	12	8	1	1	2	1
F-15	20	12	2	1	2	1
F-16	10	(a)	1	2	2	2
F-18	13	(a)	2	1	2	2
F-86	12	30	2	1	1	2
F-89	6	25	1	2	1	2
F-100	13	50	1	1	1	2
F-101	17	20	1	1	1	1
F-102	31	45	1	2	2	1
F-104	19	20	2	1	1	2
F-105	15	17	2	1	2	1
F-106	26	29	1	1	2	1
F-111	18	21	2	2	2	1
S-3	8	5	2	2	X	1
T-38	14	24	1	2	X	2
T-39	4	5	2	1	X	2

NOTE: X = values collected for fighters only.
[a]Not available.

Appendix C

DAPCA-III ESTIMATING RELATIONSHIPS

The previous set of RAND airframe CERs (DAPCA-III), documented in Ref. 3, is summarized in Table C.1.

Table C.1

DAPCA-III ESTIMATING RELATIONSHIPS[a]

	Statistics			
Estimating Relationship	R^2	SEE	F	N
$ENGR_{100} = .0234\ AUW^{.656}_{(.000)}\ SP^{.960}_{(.008)}$	.90	.26	26	9[b]
$TOOL_{100} = .472\ AUW^{.638}_{(.000)}\ SP^{.499}_{(.025)}$	.71	.41	27	25
$LABR_{100} = .353\ AUW^{.793}_{(.000)}\ SP^{.423}_{(.021)}$	.85	.34	62	25
$MATL_{100} = .0763\ AUW^{.880}_{(.000)}\ SP^{.867}_{(.000)}$	.86	.36	67	25
$DS = (.000626\ AUW^{.688}\ SP^{1.21})^{c}$	.53	.72	12	24
$= +(.0000354\ AUW^{.724}_{(.000)}\ SP^{1.92}_{(.000)})^{d}$	.68	.66	23	24
$FT = .192\ AUW^{.710}_{(.000)}\ SP^{.586}_{(.084)}\ TESTAC^{.710}_{(.001)}\ CARGODV^{1.66}_{(.011)}$	.81	.44	21	25
$QC_{100} = .085 \times LABR_{100}$ if cargo	—	—	—	—
$= .12 \times LABR_{100}$ if noncargo	—	—	—	—
$PROG_{100} = 6.22\ AUW^{.728}_{(.000)}\ SP^{.737}_{(.000)}$	.88	.27	79	24

[a]All cost elements estimated directly in dollars have been converted to 1977 levels by adjusting the initial coefficient.
[b]Post-1957 aircraft excluding A-7, KC-135, and T-39.
[c]Labor component of development support.
[d]Material component of development support.

Appendix D

COST-QUANTITY SLOPES AND LABOR RATES

COST-QUANTITY SLOPES

Minimum, maximum, and average cost-quantity slopes for the full estimating sample are shown in Table D.1. A comparison of slopes by mission type is provided in Table D.2. With two exceptions (the attack aircraft material slope and the fighter quality-control slope), the slopes show little deviation about the full sample averages. However, even changes in slope as small as 1 percentage point can have a major effect on cost. The extent of this effect will of course vary with the quantity and the slope magnitude, but for a run of 700 aircraft, a 1 percentage point increase in the slope will usually increase total costs by at least 10 percent.

Table D.1

CUMULATIVE TOTAL COST-QUANTITY SLOPES[a]

(In percent)

Item	Engineering Hours	Tooling Hours	Mfg. Labor Hours	Mfg. Material Cost	Quality Control Hours	Total Program Cost
No. of observations	34	34	34	34	22	34
Range	106–132	108–158	140–182	140–200	126–234	124–144
Average	114	122	154	172	158	134
Exponent	0.189	0.287	0.623	0.782	0.660	0.422

[a]Based on first 200 units; cumulative average slope = cumulative total slope divided by two.

Table D.2

CUMULATIVE TOTAL COST-QUANTITY SLOPES, BY MISSION TYPE

(In percent)

Sample	Engineering Hours	Tooling Hours	Mfg. Labor Hours	Mfg. Material Cost	Quality Control Hours	Total Program Cost
Total (34)	114	122	154	172	158	134
Attack (7)	110	122	154	180	154	134
Bomber/Transport (8)	116	116	154	170	152	136
Fighter (17)	116	124	156	172	170	132

Since the estimating relationships in the recommended equation set (Table 15) are based on a sample limited to post-1960 aircraft, average slopes for the post-1960 sample are also determined and compared with the full sample:

Cost Element	Full All-Mission Sample (34 aircraft) Slope (%)	Post-1960 All-Mission Sample (13 aircraft)	
		Slope (%)	Exponent
Engineering	114	112	.163
Tooling	122	120	.263
Manufacturing labor	154	156	.641
Manufacturing material	172	174	.799
Quality control	158	156	.641
Total program cost	134	132	.401

As indicated, the differences are slight and hardly a basis for drawing any conclusions about temporal changes. However, in the interest of consistency, the slopes based on the post-1960 sample are suggested for use with the recommended equation set.

Similarly, for the fighter equation set (Table 21), the slopes based on the more limited post-1960 sample are also suggested:

Cost Element	Full Fighter Sample (17 aircraft) Slope (%)	Post-1960 Fighter Sample (6 aircraft)	
		Slope (%)	Exponent
Engineering	116	112	.163
Tooling	124	120	.263
Manufacturing labor	156	158	.660
Manufacturing material	172	166	.731
Quality control	170	164	.714
Total program cost	132	128	.356

FULLY BURDENED LABOR RATES

All cost elements estimated directly in dollars are in 1977 dollars. Suggested 1977 fully burdened labor rates (and those used to estimate total program cost) are:

Engineering	27.50
Tooling	25.50
Manufacturing labor	23.50
Quality control	24.00

For estimates in 1986 dollars, the following labor rates and adjustment factors are suggested:

Engineering, $/hr	59.10
Tooling, $/hr	60.70
Manufacturing labor, $/hr . . .	50.10
Quality control, $/hr	55.40
Manufacturing material (index)	1.94
Development support (index) .	1.94
Flight test (index)	1.94
Total program cost (index) . . .	2.13

The 1986 labor rates are based on data provided by seven contractors:

Labor Category	Hourly Rates ($) Average	Range	Range About Average (%)
Engineering	59.10	47.70–70.00	−19, +18
Tooling	60.70	56.50–65.00	− 7, + 7
Mfg. labor	50.10	41.70–58.00	−17, +16
Quality control	55.40	49.10–62.60	−11, +13

Note that with the exception of tooling, the range about the average rate is at least ±10 percent. This range could arise from differences in accounting practices, business bases, or capital investment. Irrespective of cause, however, labor-rate variation is one more component of a larger uncertainty which already includes the error associated with statistically derived estimating relationships and questions about the proper cost-quantity slope. Furthermore, in addition to the intercontractor differences, these rates are also subject to temporal change—accounting procedures, relative capital/labor ratios, etc. Thus, the 1986 fully burdened rate is qualitatively different from the 1977 rate. Unfortunately, trying to estimate the magnitude of such quality changes, even very crudely, is a study in itself and beyond the scope of this analysis.

The material, development support, and flight-test escalation indexes are based on data provided in AFR 173-13.[1] For 1977–1984, the airframe index presented in Table 5-3 (Historical Aircraft Component Inflation Indices) of AFR 173-13 was used. For 1985 and 1986, the aircraft and missile procurement index presented in Table 5-2 (USAF Weighted Inflation Indices Based on OSD Raw Inflation and Outlay

[1]See Ref. 35.

Rates) was used. The total program cost adjustment factor was then determined on the basis of a weighted average (at Q = 100) of the individual cost elements.

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This report presents generalized equations for estimating the development and production costs of aircraft airframes. It provides separate cost estimating relationships (CERs) for engineering, tooling, manufacturing labor, and quality-control hours; manufacturing material, development support, and flight-test cost; and total program cost. The CERs, expressed in the form of exponential equations, were derived from a database consisting of 34 military aircraft with first flight dates ranging from 1948 to 1978. In addition to the basic objective of developing an updated set of airframe CERs, the study also examined three specific possibilities for improving CER accuracy: (1) stratifying the full estimating sample into subsamples representing major differences in aircraft type; (2) incorporating variables describing program structure and airframe construction characteristics; and (3) for the fighter aircraft only, incorporating an objective technology index into the equations.